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LIMESTONE AND LIMESTONE-LIME NEUTRALIZATION OF ACID MINE DRAINAGE

Roger C. Wilmoth

Environmental Protection Agency
Rivesville, West Virginia

June 1974

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By

Roger C. Wilmoth
Mining Pollution Control Branch
Industrial Waste Treatment Research Laboratory

Program Element No. 1BB040

NATIONAL ENVIRONMENTAL RESEARCH CENTER
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
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FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment--air, water, and land. The National Environmental Research Centers provide this multidisciplinary focus through programs engaged in

- studies on the effects of environmental contaminants on man and the biosphere, and
- a search for ways to prevent contamination and to recycle valuable resources.

This report defines the important parameters for the use of limestone, hydrated lime, and combination limestone/lime treatment of acid mine drainage discharges containing iron in predominately the ferric state.

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National Environmental
Research Center, Cincinnati

ABSTRACT

The critical parameters affecting neutralization of ferric-iron acid mine waters were characterized by the U.S. Environmental Protection Agency in comparative studies using hydrated lime, rock-dust limestone, and a combination of the two as neutralizing agents. The advantages and disadvantages of each of these neutralizing agents were noted. On the ferric-iron test water, combination limestone-lime treatment provided a better than 25-percent reduction in materials cost as compared to straight lime or limestone treatment. Significant reduction in sludge production was noted by the use of rock-dust limestone and by the use of combination treatment as compared to hydrated-lime treatment. Emphasis on optimizing limestone utilization efficiencies resulted in an increase from approximately 35-percent to 50-percent utilization. Studies using limestone that had been ground to pass a 400-mesh screen resulted in utilization efficiencies near 90 percent.

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SECTION I

CONCLUSIONS

Reaction time, effluent pH, mixing chamber design, reagent particle size, and temperature were identified as critical parameters affecting the limestone treatment process for neutralizing acid mine drainage (AMD). Reaction times of 20 to 30 minutes appeared optimum. Decreasing the effluent pH increased limestone utilization efficiency. Use of 14-mesh wire screen reactor baffles abraded reaction coatings from limestone particles and increased both mixing efficiency and limestone utilization efficiency. Although 400-mesh limestone was clearly superior in reactivity to rock-dust limestone (approximately 100 mesh), the commercial scarcity of 400-mesh stone would make rock dust the logical choice. The economics of onsite grinding should be further investigated, however. Use of a shallow holding pond may increase water temperature and thus enhance limestone efficiency. Use of such a pond would be discontinued during cold months.

Maximum utilization efficiency observed during continuous-flow, pH 5.0 studies using rock dust was in the area of 60 percent (or 1.7 times the stoichiometric requirement). Continuous-flow studies at pH 6.5 resulted in efficiencies of about 50 percent (or twice the stoichiometric requirement).

Studies at pH 6.5 using 400-mesh limestone yielded utilization efficiencies above 90 percent (or 1.1 times the stoichiometric requirement).

Sludge recycling studies provided no quantitative conclusions since continuous recycling facilities were not available and the attempted arrangement was not entirely satisfactory. However, limestone utilization efficiency was improved sufficiently to warrant its further investigation as a highly promising technique.

Hydrated-lime treatment appeared to be more economical than the optimum case of limestone treatment, but the advantages of the more dense limestone sludge may offset the initial cost advantage of lime treatment.

Combination rock-dust limestone -- hydrated-lime treatment, which must be accomplished in two separate stages, worked most satisfactorily with a first-step (limestone) pH near 4. Subsequent lime treatment of the partially neutralized water could be taken to any desired pH, thus making the process amenable to ferric and ferrous iron situations. Reaction times of 20 to 30 minutes were required for efficient utilization of limestone in the first step of treatment. For second-stage lime treatment, 10 to 15 minutes of reaction time were sufficient.

Combination limestone-lime treatment of ferric acid mine drainage produced half the sludge volume of lime treatment alone although slightly more than limestone treatment alone. The solids content of the sludge from combination treatment was five times as great as that produced by lime treatment, though significantly less than that produced by limestone treatment.

The combination process has significant potential for reducing the cost of AMD treatment. On the ferric-iron test water, a better than 25-percent reduction in material cost was achieved by using combination treatment instead of straight lime or straight limestone alone. Water quality of the effluents from all three processes was comparable.

A lime/limestone raw-material cost ratio of 1.8:1 was the break-even point on the test water where no economic advantage would be achieved by using limestone-lime rather than lime alone. As the ratio increased, so did the cost advantage of combination treatment.

Increasing the final treatment pH slightly decreased combination treatment's economic advantage but combination treatment should still be economically beneficial in ferrous iron situations.

SECTION II

RECOMMENDATIONS

An economic study should be undertaken to determine the feasibility of grinding limestone at the treatment plant to 400-mesh size.

Limestone sludge recycling should be fully investigated on equipment designed specifically for recycling applications.

The limestone-lime process should be demonstrated on ferrous-type waters.

Work should be done on sludge disposal techniques and related costs.

SECTION III

INTRODUCTION

With the advent and enforcement of stronger pollution laws, the coal mining industry has begun an extensive program of acid water treatment plant design and construction. To date, Pennsylvania, the state which ranked third[1] in coal production for 1970, has approximately 200 deep-mine treatment plants in operation.[2] Less than 50 of these are highly sophisticated, large-scale plants. The number one and two coal producers, West Virginia[3] and Kentucky[4] have 35 and 5 acid mine drainage (AMD) treatment plants in operation respectively. Virtually all of these plants use lime as the neutralizing agent.

Lime neutralization has several significant disadvantages: high raw-material cost, hazardous nature of the material itself, high potential for accidental overtreatment, and production of a high-volume, low-density sludge. The state of the art of straight lime neutralization is fairly well known at this time.

The U.S. Environmental Protection Agency (EPA) and other researchers have investigated other neutralizing agents such as limestone, soda ash, sodium hydroxide, sodium sulfide, and combinations of these in attempts to improve the AMD treatment process.

In 1970, Wilmoth and Hill[5] investigated soda ash and found it too expensive for general treatment-plant applications. Care and Zawadzki[6] (1965) and Zawadzki and Glenn[7] (1968) studied sodium sulfide and hydrogen sulfide -- limestone treatment of AMD; they indicated sodium sulfide costs would generally prohibit its use. Due to high raw-material costs, sodium hydroxide would not only be too expensive but is also hazardous to handle.

Use of limestone has been touched on by a variety of investigators. Earlier work by Braley et al. (1951)[8]; Clifford and Snarley (1954)[9];

Glover (1967)[10]; Zurbach (1963)[11]; Wheatland and Borne (1962)[12]; Chamberlain (1968)[13]; Hoak et al. (1945)[14]; Deul and Mihok (1967)[15]; Calhoun (1968)[16]; Wilmoth and Hill (1970)[18]; and Holland et al. (1970)[19] laid the groundwork for present investigation. These researchers pointed out that limestone has certain inherent advantages over lime for AMD treatment; e.g., lower raw-material cost, less hazardous material to handle, marginal problems resulting from accidental overtreatment, and dense, low-volume sludge production. The major disadvantages cited were the inability of limestone to produce a pH above 7 (necessary for rapid, efficient iron oxidation) and the low utilization efficiencies that resulted in excess limestone usage.

Ford, Boyer, and Glenn[20] of Bituminous Coal Research, Inc. (BCR) approached the limestone--ferrous iron application problem by recycling sludge in a 0.5-gpm (1.9 l/min), continuous-flow, lab-scale system. Using a 100-percent excess of powdered limestone (50 percent utilization efficiency) and a 1:1 ratio of sludge-slurry-recirculation flow to AMD feed flow, they were able to reduce the effluent iron concentrations from 80 mg/l to below 7 mg/l. BCR was confident that their recirculation process could effectively treat AMD waters with ferrous-iron concentrations below 500 mg/l. A major disadvantage to their process was that a 60-minute reaction time was required to achieve the desired results. This reaction time would be expensive in terms of tank size and mixing costs for large flow situations. Another important contribution of Ford, Boyer, and Glenn was characterizing the type of limestone most effective in AMD treatment. They designed a simple test for field use in evaluating limestones for the user's particular application.[20] In general, the most desirable stones have small particle size, are virtually pure calcium carbonate, and/or are mostly calcite and have a large surface area. Dolomitic limestones were found to be significantly ineffective in AMD treatment.

Dr. Lovell of Pennsylvania State University used a unique approach to the ferrous iron situation in work at the Penn State - EPA Hollywood Facility. Using a rotary attrition-reaction mill and coarse rather than

powdered limestone, Lovell claimed[21] [22] limestone utilization efficiencies in excess of 80 percent and observed across-the-board reductions in ferrous content as high as 80 percent, using AMD sources with initial ferrous concentrations near 100 mg/l.

An 80-percent reduction in the 100 mg/l ferrous concentration still did not meet the State water quality standards of Pennsylvania, however, since the effluent iron was in excess of 7 mg/l. Detention time in the rotary reactor was approximately 2 minutes. Lovell later used biological oxidation as a pretreatment to limestone neutralization in this flow scheme (at 18°C), and an initial ferrous concentration of 374 mg/l was reduced to 26 mg/l by a trickling filter-type, surface biological reactor with a detention time of 5 minutes. Subsequent limestone neutralization by the rotary mill reduced the ferrous content to 20 mg/l and increased the pH to 6.2-6.6. Additional oxidation occurred in the settling lagoon, and the discharged effluent contained only 6 mg/l of ferrous iron. The rotary-mill approach first tried on AMD by Zurbach[11], and later by Mihok and Chamberlain[13], was improved by Lovell, who demonstrated its promise in AMD treatment schemes for ferric situations. For most ferrous situations, some method of preoxidation must be employed to improve economics. The biological oxidation scheme was demonstrated by Lovell to have significant promise. As in any biological system, upsets due to temperature or water quality variations were inevitable but were felt to be solvable problems.

The EPA approach to date has been to attempt to improve the utilization efficiency of limestone in treatment of waters where the iron is already in the ferric state since it was felt that straight limestone treatment of ferrous waters would have little chance of economically competing with lime. Also, EPA pursued the suggestion of Holland, et al.[19], and others and developed a two-stage, combination limestone-lime treatment process that offers significant advantages over both lime treatment and limestone treatment alone and that should have direct application to ferrous iron situations. Results of the EPA investigations (conducted at EPA's Mine Drainage Treatment Field Site at Norton, West Virginia) are presented in this report.

Yocum and Grandt of Peabody Coal Company are planning to demonstrate the latest limestone, lime, and combination limestone-lime treatment techniques on a large scale (2000 gpm or 7600 l/min) under EPA sponsorship (Grant 14010 DAX). As of this report, operational difficulties have delayed initiation of research on their ferric-type water.

EPA is continuing work on the combination process using a highly-polluted ferrous AMD discharge at the Crown Mine Drainage Control Field Site near Morgantown, West Virginia.

SECTION IV

PROCEDURES

DEFINITIONS

Definitions and an explanation of the calculations used in this report are presented under Section VIII, Glossary.

TEST EQUIPMENT

A schematic drawing of the dual neutralization system used is presented in Figure 1. Water was pumped from Grassy Run, a stream heavily polluted with AMD, through a pressurized sand filter. The filter removed large particulate matter that in past experiences have tended to clog the flow control valves and thus vary the water flow. In a full-scale operation, this filter would not be required.

From the filter, the water went to a 500-gallon (1890-liter) supply tank. By maintaining a continuous overflow, liquid level in the tank was held constant, and a constant discharge rate could be maintained. Globe valves were used to adjust flows into two separate 150-gallon (568-liter), stainless-steel reaction tanks equipped with flash mixers and two 14-mesh, stainless-steel screen baffles. The baffles, in addition to decreasing reactor short-circuiting, served to increase limestone reaction efficiency by abrading the particles of limestone as they passed through the screen. It was assumed that the screen did two things: first, limestone particle size was reduced somewhat by collision with the screen; and second, reaction products such as ferric hydroxide and calcium sulfate were abraded from the particle surface thus exposing fresh reactive areas.

By having a dual system such as this, it was possible to use one side as a control and the other side as the variable and thus expedite the research efforts. One side of the system was referred to as Process A and the other as Process B. The dual system allowed immediate evaluation of the isolated variable under study.

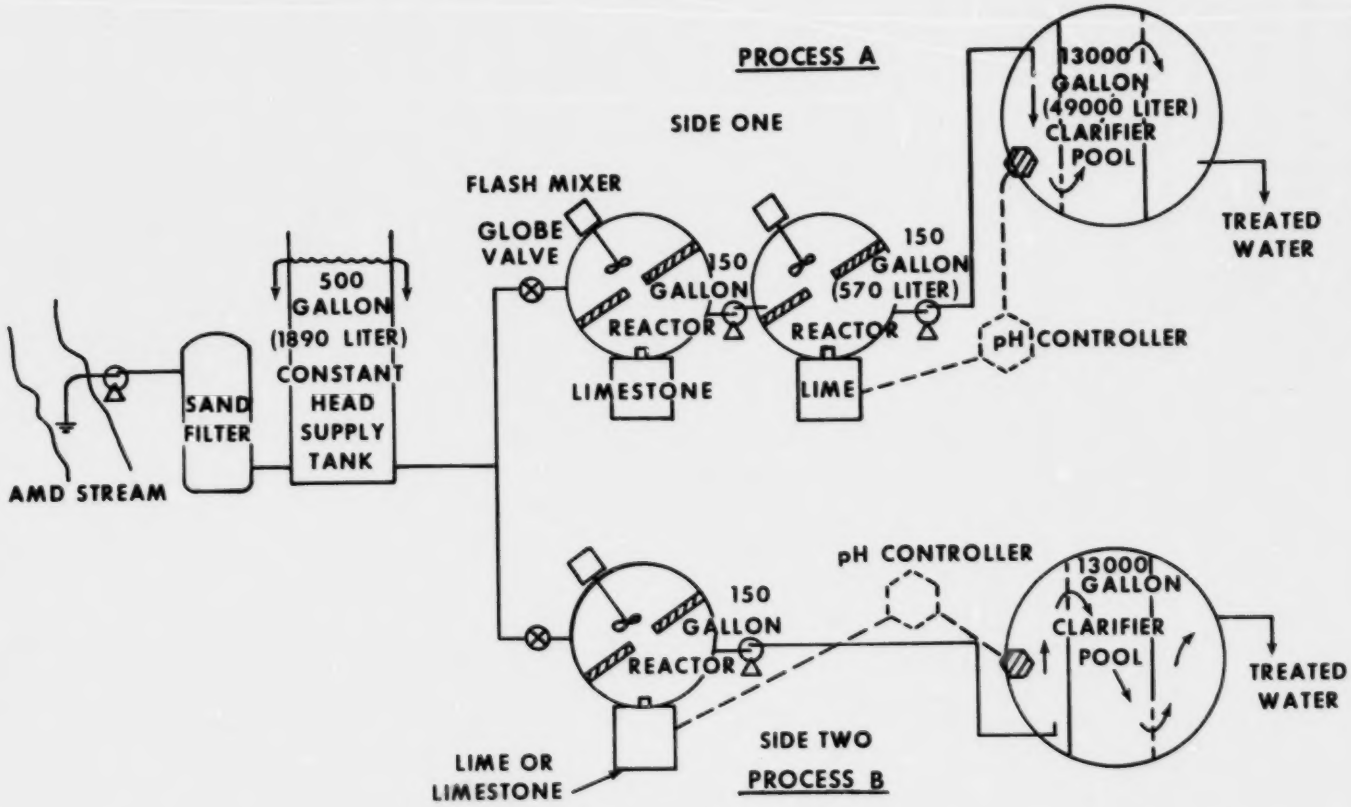


Figure 1. Schematic flow diagram of the dual neutralization system.

BIF helix-type dry feeders were used to add hydrated lime and rock-dust limestone to the reactors. These feeders were controlled automatically by pH controllers whose probes were located in the settling pools.

The neutralized waters from Process A and Process B were pumped into identical pools for sludge separation. These pools held approximately 13,000 gallons (49,000 liters) each and were 4 feet (1.36 meters) deep. Two baffles were installed in each pool to decrease short-circuiting and improve settling. Canvas covers, sidewall insulation, and infrared heat lamps kept the pools operational during winter.

Continuous sludge removal from the pools was not possible because of pool design, so periodic pumping was required. This task was performed at the end of each test run (generally 7 days in length).

Maximum flow capacity of each side of the system was 15 gpm (21,600 gpd) or 56.8 l/min (82,000 l/day). Flow rates were varied from 5 to 15 gpm (18.9 to 56.8 l/min) to study the effects of reaction time on system efficiency.

PHYSICAL MEASUREMENTS

Water flow rates were determined volumetrically in a 15-gallon (56.8-liter) container. Reagent usage was calculated by collecting and weighing five one-minute samples from the dry feeder, determining the average weight per minute, and multiplying by the number of minutes of operation. Dual elapsed time meters reading in minutes and tenths and equipped with dynamic braking circuitry recorded the operating time for each dry feeder. Though pH was automatically controlled, frequent probe cleaning and operator attention was required for precise process control.

Reactor and clarifier detention times were determined by instantaneously injecting salt and continuously monitoring effluent conductivity until it returned to base level. Mean probable detention times were determined by logarithmic probability plots of the resulting conductivity data. A summary of typical detention times is given in Table 1.

Table 1. TYPICAL DETENTION TIMES

Flow rate, gpm	Reactors			Settling pools		
	Mean probable detention time, minutes	Theoretical[a] detention time, minutes	Efficiency[b] percent	Mean probable detention time, hours	Theoretical[a] detention time hours	Efficiency[b] percent
5	19.1	21.0	91	23.4	39	60
10	9.1	10.5	87	10.5	19.5	54
15	5.7	7.0	82	5.2	13	40

[a] Theoretical detention time = volume ÷ flow rate.

[b] Efficiency = mean probable time ÷ theoretical X 100.

Note: The effective capacity of each reactor is 105 gallons.
The effective capacity of each settling pool is 11,700 gallons.
To convert from gpm to liters/minute, multiply by 3.785.

Sludge settling rates were difficult to determine, since a definite supernatant/sludge interface never clearly developed during settling. During the early part of this research, the position of the interface was estimated to determine the settling curves. Later, it was decided to measure supernatant turbidity as a function of time in lieu of estimating the interface position. Sludge was therefore allowed to settle undisturbed in 1000-ml graduated cylinders, and supernatant turbidity was periodically measured. It was possible to read the sludge buildup in the bottom of the graduate even though the settling interface never clearly developed.

PROCEDURES FOR CHEMICAL ANALYSES

Conductivity and pH were measured potentiometrically. Total iron, aluminum, magnesium, and calcium were determined by atomic absorption spectrophotometry.[23] EPA methods[23] were used for sulfate, total solids, alkalinity, and turbidity determinations. The Salotto[24] acidity method was used in which hydrogen peroxide is added to oxidize the metals; a cold titration is then made to pH 7.3.

CHARACTERISTICS OF REACTANTS

AMD from Grassy Run was treated in these studies (Table 2).

Table 2. GRASSY RUN WATER QUALITY DATA, 1971

Parameter	Unit	Mean[a]	Maximum	Minimum	Standard Deviation
pH	pH	2.8	3.4	2.5	---
Specific conductance	Mmhos/cm	1100	2240	340	415
Acidity as $CaCO_3$	mg/l	430	640	130	125
Calcium	mg/l	106	170	18	49
Magnesium	mg/l	35	120	21	12
Aluminum	mg/l	33	69	18	12
Sulfate	mg/l	590	1200	76	260
Iron (Total)	mg/l	92	170	14	39
Temperature	^{o}F	48	57	39	5.4
Flow	CFS[b]	10.8	40	1.8	9.4

[a] Median value.
[b] To convert from CFS to cu m/sec, multiply by 0.028.

Grassy Run is a small, heavily polluted stream in which an estimated 90 percent of the flow emanates from abandoned coal mines. Approximately 70 percent of this pollutant flowed directly out of underground mines.[5] Some sewage is also present in the creek. Virtually all iron was in the ferric state.

The limestone and hydrated lime used in this study were obtained from Germany Valley Limestone Company, Riverton, West Virginia. In order to obtain the smallest particle size commercially available, the rock-dust form of limestone was used. All tests in this study were made using the hydrated form of lime.

Table 3 presents the manufacturer's chemical analyses an' cost for lime and limestone. A spectrochemical analysis of the limestone was made by BCR and is reported in Table 4.

Table 3. MANUFACTURER'S CHEMICAL ANALYSES OF REAGENTS

Parameter	Hydrated lime,[a] min. percent comp.	Rock-dust limestone,[b] min. percent comp.
CaO	72.00	53.0
MgO	0.40	0.38
$CaCO_3$ equivalent	130	98.8
SiO_2	-	0.49

[a]Lime cost $18.00/ton ($19.85/metric ton) in bags or 0.90 cents/lb (1.985 cents/kg).

[b]Limestone cost $6.00/ton ($6.61/metric ton) in bags or 0.30 cents/lb (0.66 cents/kg).

Table 4. SPECTROCHEMICAL ANALYSIS[a] OF GERMANY VALLEY LIMESTONE[25]
(percent)

Loss on ignition	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	TiO_2	Na_2O	K_2O	MnO_2
43.0	1.0	0.43	0.15	1.16	97.0	0.04	0.02	0.1	0.03

[a]X-ray analysis identified only one compound --$CaCO_3$ (96.5%).

Sieve analyses of as-received lime and limestone are presented in Table 5.

Table 5. SIEVE ANALYSES (DRY) OF AS-RECEIVED LIME AND LIMESTONE

Screen size	Hydrated lime, percent passing	Rock-dust limestone, percent passing
50 mesh	96.2	99.1
100 mesh	24.3	58.7
200 mesh	2.8	28.3
400 mesh	0.9	9.7
Percent not passing sieve	3.8	0.9

SECTION V

RESULTS

OPTIMIZING LIMESTONE TREATMENT

The limestone investigations basically followed the research plan outlined in Table 6. Each of the variables listed was investigated independently first, and then cross-checked against other variables to insure that the parameter under study exhibited consistent behavior under a variety of conditions.

Table 6. RESEARCH PLAN FOR LIMESTONE INVESTIGATIONS

Order of study	Variable	Action investigated
1	pH	Effect on utilization efficiency
2	Detention time	"
3	Temperature	"
4	Reactor baffles	"
5	Particle size	"
6	Limestone feed: dry vs slurry	"
7	Limestone feed: one vs two steps	"
8	Sludge recycle	"

Some of the initial studies on the variables were performed on batch scale equipment. When warranted, results of batch studies were also demonstrated under continuous-flow conditions.

Effect of pH

Titration curves for limestone and lime on the Grassy Run water had been developed earlier[5] and are presented in Figure 2. Limestone's

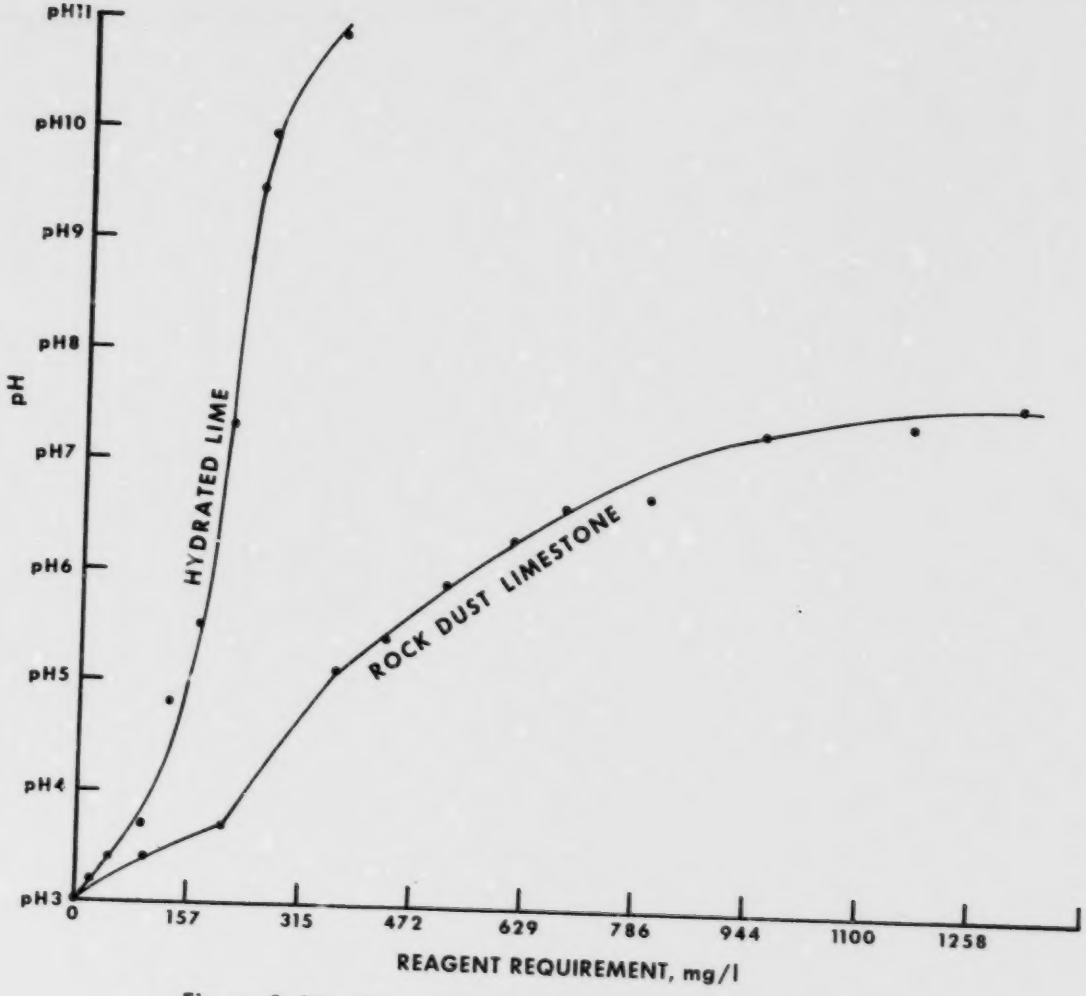


Figure 2. Titration curves for limestone and lime.

titration curve indicated approximately 1.8 times as much limestone was required to neutralize to pH 6 than to pH 5 and 4 times as much was required to neutralize to pH 7 than to pH 5. To treat to pH 7 would thus require excessive limestone. Earlier tests[5] had shown that the iron concentration could be reduced to less than 7 mg/l at pH's above 5. Most of the limestone testing was done at pH 5 for two reasons:

1. The effluent quality was generally acceptable with the exception of pH; and
2. The limestone reaction was quite sensitive in the pH 5 area of the titration curve. This sensitivity made the reaction more amenable to precise control techniques, thus resulting in increased reliability and precision.

Several continuous-flow tests were made at 15 gpm (56.8 1/min) at various pH levels. This flow rate corresponded to 5.7-min reaction time and 5.2-hr settling time. No reactor baffles were used. Results of the pH runs (Table 7) confirmed that iron concentrations meeting the Pennsylvania requirement of 7 mg/l could be obtained at pH 5.

Table 7. EFFECT OF pH ON EFFLUENT IRON, EFFLUENT TURBIDITY AND LIMESTONE REQUIREMENT[a]

pH	Limestone usage, (lbs/1000 Gal)[b]	Effluent Quality		
		Iron, (mg/l)	Turbidity, (JTU)	Alkalinity, (mg/l)
5.1	6.59	2.3	53	1
5.6	9.06	4.0	44	2
6.1	9.70	2.3	29	24
7.0	11.11	0.7	10 (est)	78

[a]Data recorded 4/28/70. Flow rate: 15 gpm (56.8 1/min) or 5.7-min detention time; initial acidity range: 440-470 mg/l. No reactor baffles were used.

[b]To convert lbs/1000 gal to kg/cu m, multiply by 0.120.

Neutralizing to pH 6 instead of to pH 5 required 1.5 times as much limestone (compared to 1.8 in the titration curves). Only 1.7 times as much was needed to neutralize to pH 7 instead of to pH 5 in the continuous-flow tests (compared to four times as much in the titration tests). This difference was attributed to the longer detention times provided in the continuous-flow settling pool. Chemistry data for this study are presented in Table 35 of the Appendix.

In summary, optimum limestone usage was observed in the pH range of 5.0 to 5.5; at higher pH's, the usage was progressively less efficient.

Effect of Detention Time

Detention time was evaluated by operating each side (Process A and Process B) of the dual system at different flow rates and then by putting two reactors in series as opposed to a single reactor. Table 8 summarizes the results of the detention tests. Since the tests were made at different times, the raw water quality characteristics varied; therefore, the variation in limestone usage from one test to another was due to these raw water quality changes.

Results shown in Table 8 indicate that increasing the detention time decreased limestone usage. The 19.4 percent reduction indicated in the extreme case of two reactors in series at 5 gpm (18.9 l/min) vs. one reactor at 15 gpm (56.8 l/min) -- detention times of 43 minutes vs. 5 minutes -- illustrates the strong time dependence of the limestone reaction.

Data from these and later tests are included in Figure 3. Detention times of 20 to 25 minutes appear to be optimum, since large increases in reaction time beyond this point produce only minimal gains in efficiency.

Chemistry data summaries for this study are presented in Table 40 of the Appendix.

Effect of Temperature

A series of batch tests was used to determine the effect of temperature on the utilization efficiency of limestone. The tests were made during a very cold period to establish the lower points on the graph

Table 8. EFFECT OF DETENTION TIME

Test Conditions Process A vs. Process B	Process A Limestone Usage, #/1000 Gallons	Process B Limestone Usage, #/1000 Gallons	Percent Reduction in Usage	Was observed difference statistically significant?	Appendix Table Number
15 gpm vs. 10 gpm (5 min. vs. 8 min.)*	7.50	6.82	9.1	Yes	36
15 gpm vs. 5 gpm (5 min. vs. 17 min.)*	7.01	6.11	12.8	Yes	37
Two reactors in series @ 15 gpm vs. one @ 15 gpm (14 min. vs. 5 min.)*	4.83	5.23	7.6	Yes	38
Two reactors in series @ 5 gpm vs. one @ 15 gpm (43 min. vs. 5 min.)*	6.77	8.40	19.4	Yes	39

*Mean Probable Detention Time

Note: To convert from gpm to liters/minute, multiply by 3.785.
To convert from lbs/1000 gal to kg/cu m, multiply by 0.120.

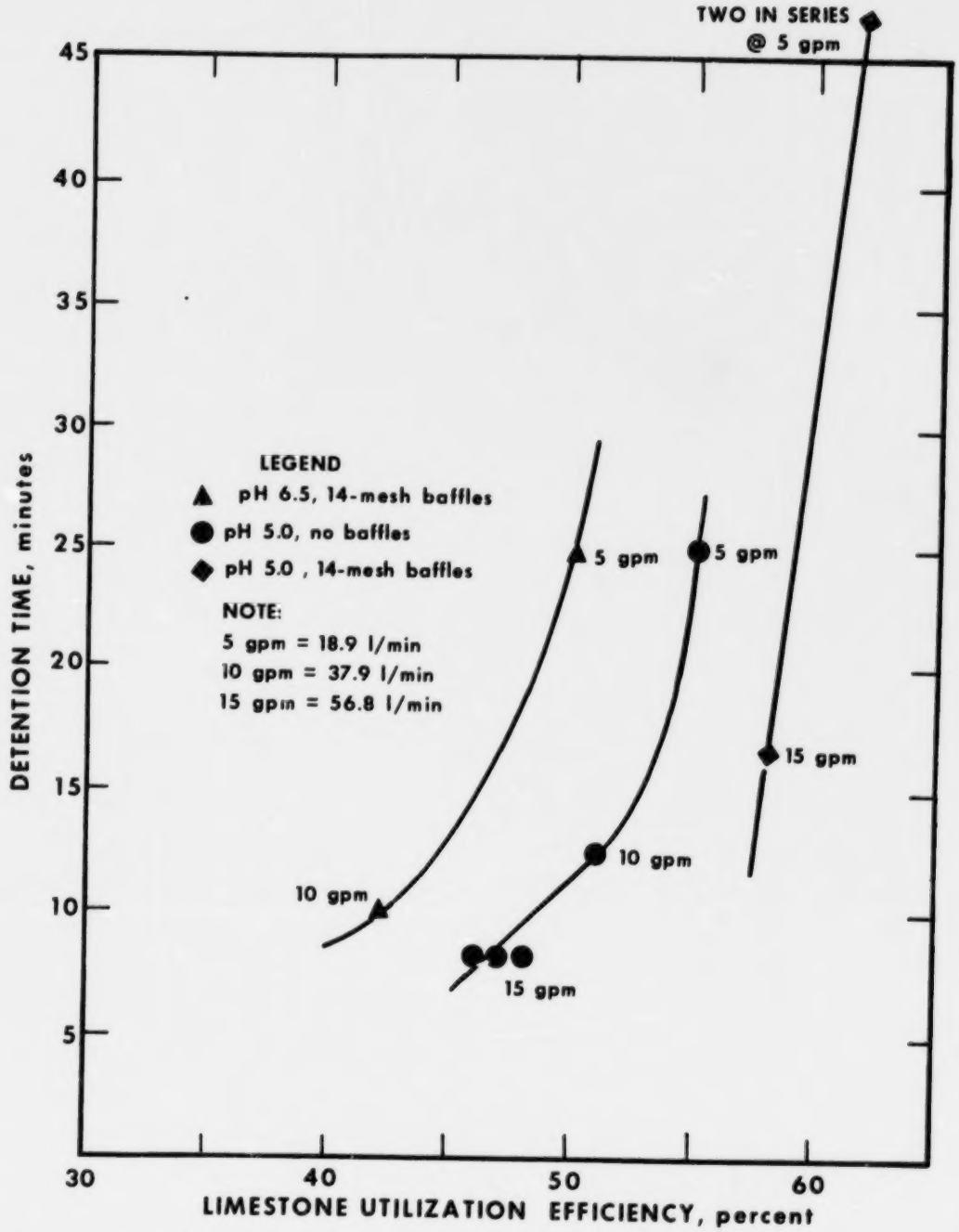


Figure 3. Effect of detention time on limestone utilization efficiency.

(Figure 4). Electric immersion heaters were used to elevate the temperature to define the remainder of the graph. Each batch test had 40-minutes reaction time and all effluent pH's were in the pH 6.2 to 6.6 range.

The effect of temperature was slight until it exceeded approximately 13°C (55°F). Between 13°C and 20°C, a noticeable increase in limestone utilization efficiency occurred. The efficiency at 20°C was 1.7 times that at 11°C. No further increase in efficiency was observed at temperatures above 25°C.

The above series of tests was repeated using limestone that had been ground to 99.6 percent passing 400-mesh and the results are shown in Figure 5. Efficiencies of the 400-mesh limestone were roughly 1.4 times (28 percent) higher than the regular rock-dust limestone. The general trend of the curves was the same, however.

Since mine drainage is discharged from underground mines at 10 to 12°C, heating the water prior to limestone treatment would be advantageous. Such a step would probably be uneconomical, however, except during the summer months when a shallow holding pond could be used for the influent water.

The 90-percent plus efficiencies seen in the 400-mesh limestone at 20°C (Figure 5) were the highest efficiencies ever obtained with batch-scale limestone treatment in these studies.

Data collected from continuous-flow tests made later in the study are presented in Figures 6 and 7 to illustrate the observed effects of temperature on limestone utilization efficiency. The effect of temperature was not as pronounced under continuous-flow conditions as it was in the previous batch-scale studies. Possibly the longer reaction times for the batch tests account for this difference. The effect of temperature was still quite strong in both cases, however.

Effect of Baffles

The use of baffles was initially investigated as a means of improving mixing and thus increasing effective detention times. Three baffle systems were tested: wooden, small-mesh screen (30-mesh), and large-mesh

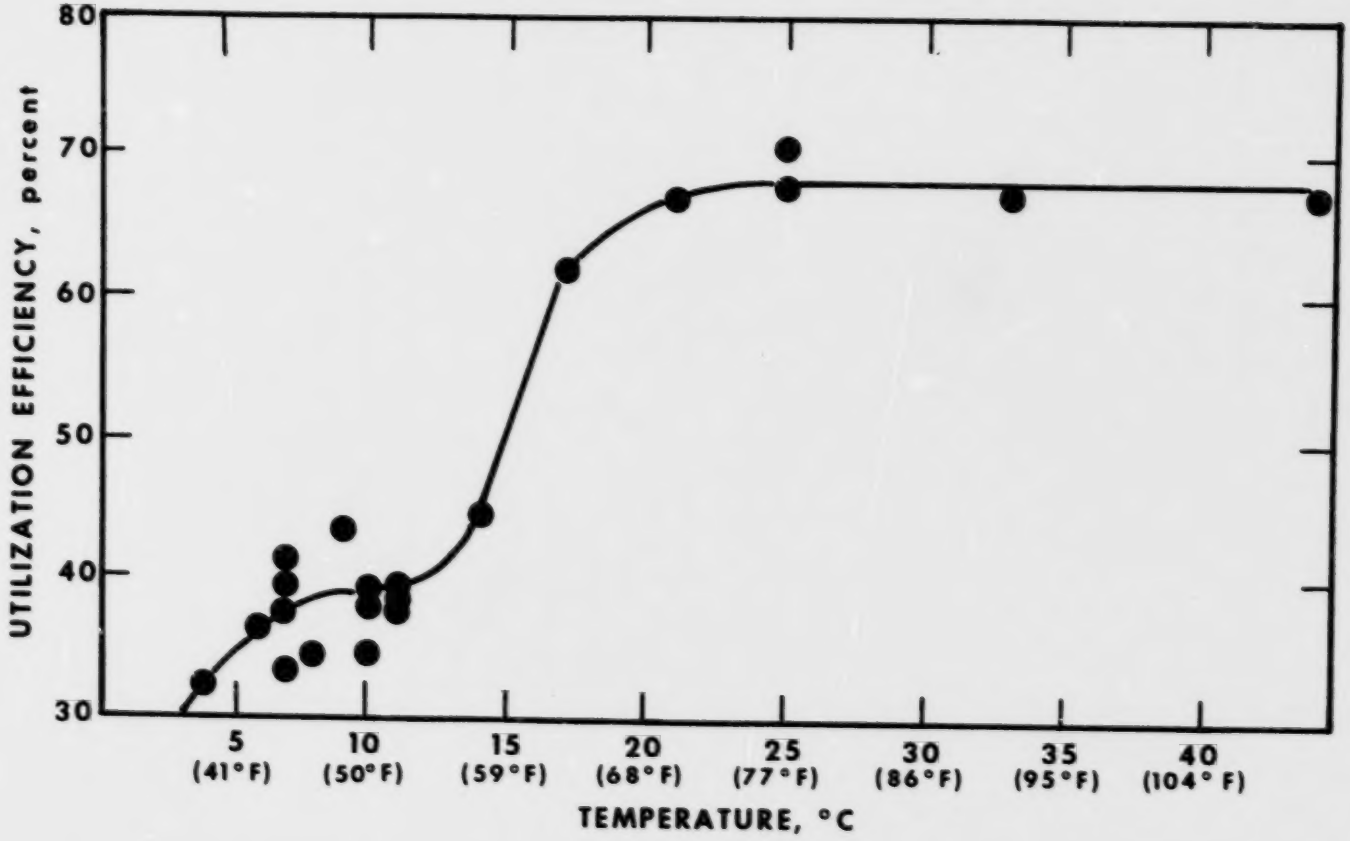


Figure 4. Effect of temperature on limestone utilization efficiency (batch tests).

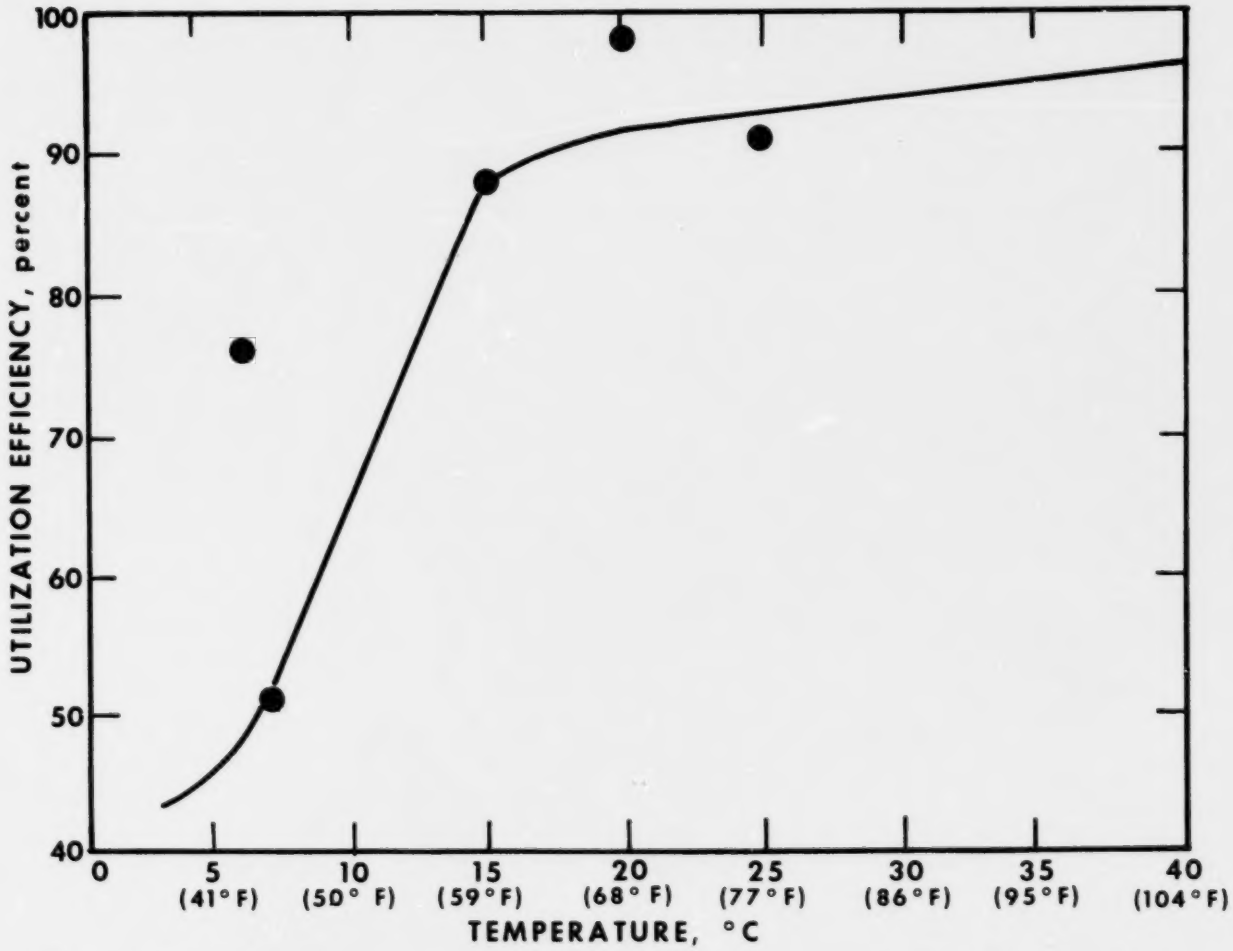


Figure 5. Effect of temperature on 400-mesh limestone utilization efficiency (batch tests).

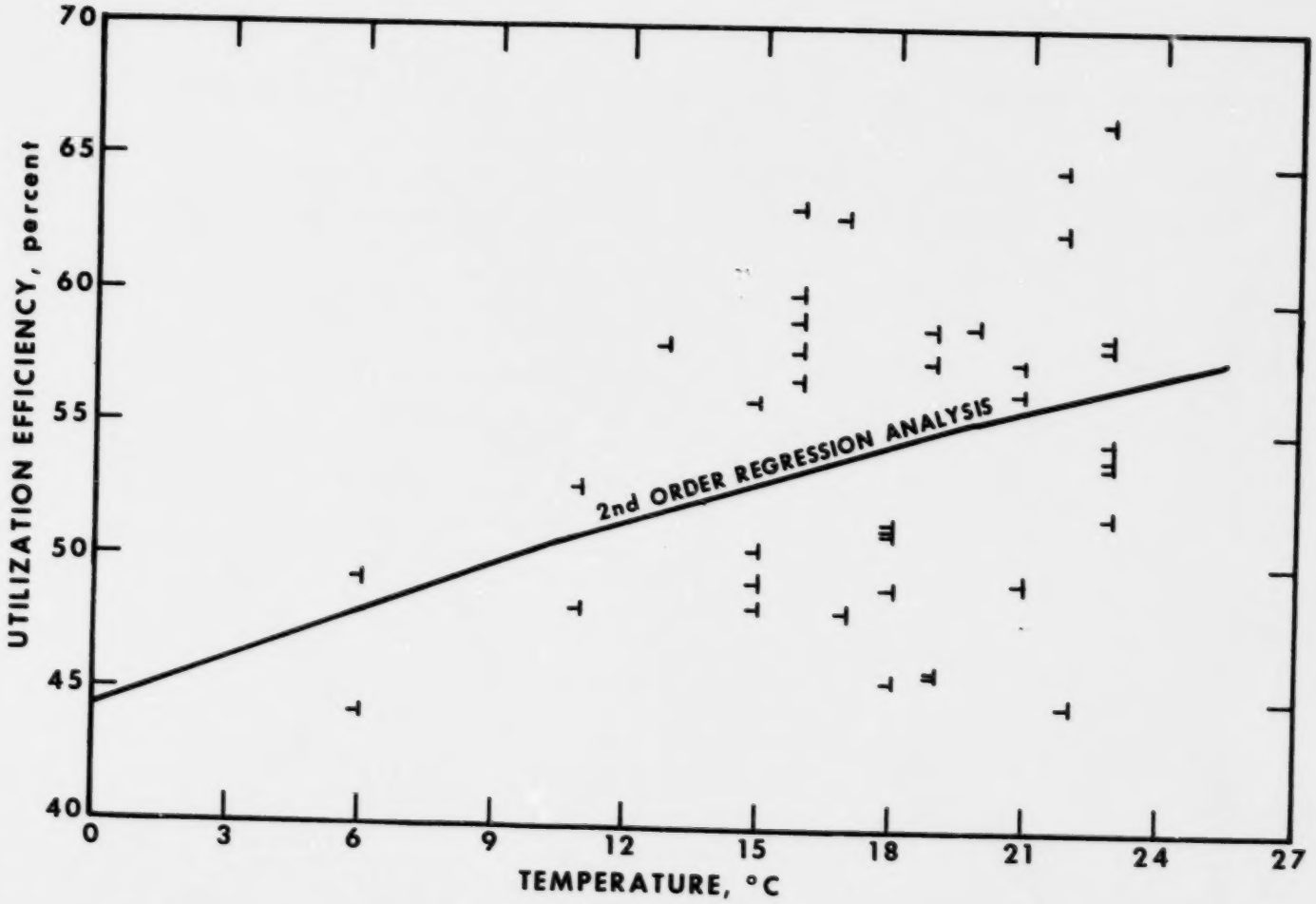


Figure 6. Effect of temperature on limestone utilization efficiency @ pH 6.5 and 5 gpm (18 .9 l/m) during continuous-flow studies.

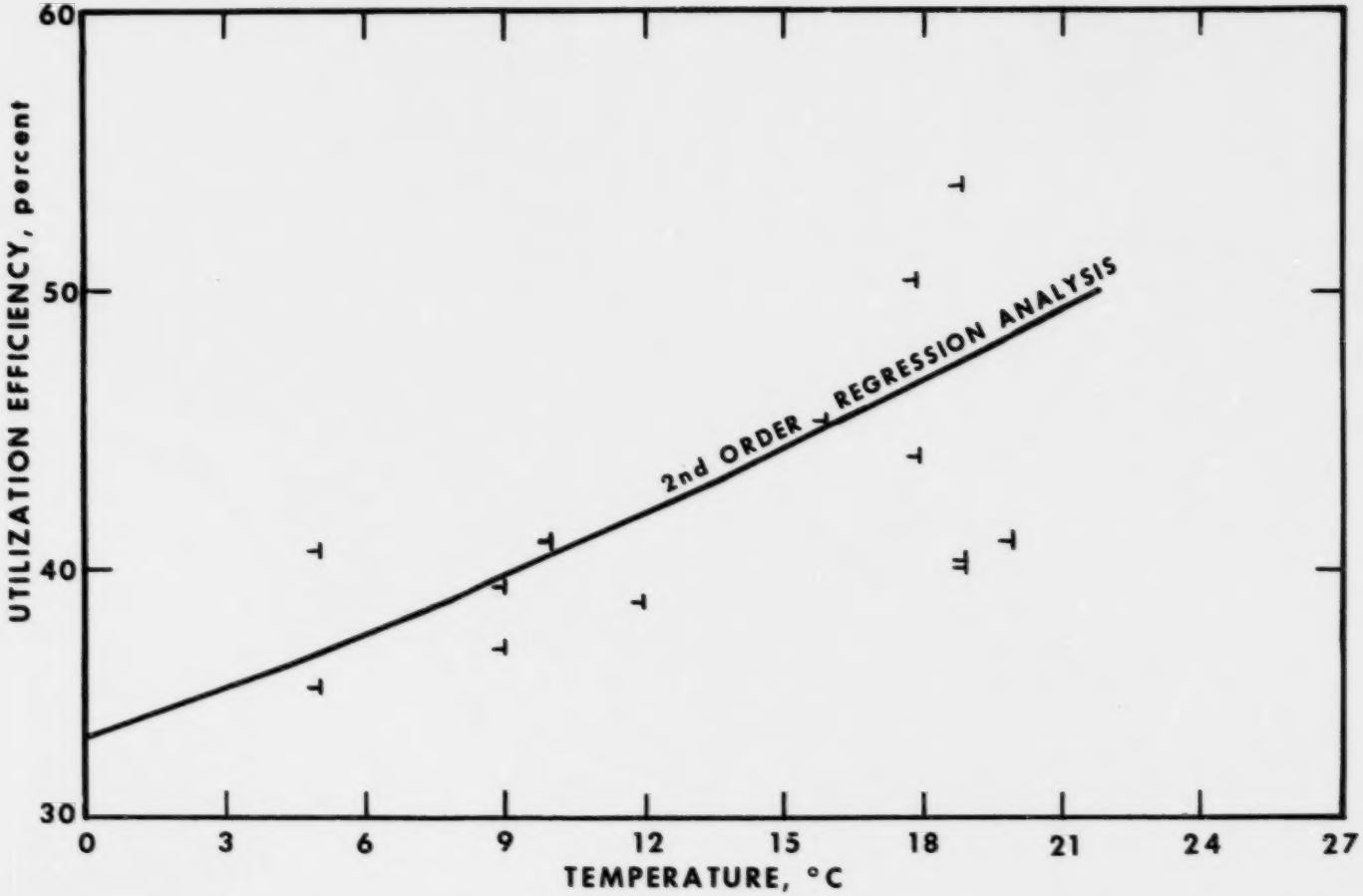


Figure 7. Effect of temperature on limestone utilization efficiency @ pH5.0 and 15 gpm (56.8 l/m) during continuous-flow studies.

screen (14-mesh). A summary of the effects of the baffles on mean probable detention times is given in Table 9. Wooden baffles increased mixing efficiency more effectively than either of the wire-mesh baffles.

The effectiveness of various baffle configurations on limestone usage is summarized in Table 10. Wooden baffles were more effective than no baffles because of an increase in detention time. Small-mesh wire baffles were slightly better than wooden baffles, even though their mixing efficiency was somewhat poorer. Large-mesh wire screen baffles improved limestone usage more than the small-mesh screen. Use of three rather than two large-mesh baffles showed little or no advantage.

Figure 8 shows the wire-mesh baffle arrangement used. It was concluded that wire-mesh baffles increased limestone utilization efficiency by:

1. Removing coatings (probably iron hydroxide) from the surface of the limestone particles by abrasion against the wire screen;
2. Improving mixing efficiency and thus increasing detention time and decreasing short circuiting; and
3. Possibly breaking the limestone into smaller particles (no tests were made to confirm this, however).

At a flow rate of 15 gpm (56.8 l/min), typical limestone utilization efficiencies for the study were as follows:

	Percent
No baffles	52
Two wooden baffles	56
Two small-mesh wire baffles	58
Two large-mesh wire baffles	60

Chemistry summaries for this study are presented in Table 45 of the Appendix.

Effect of Particle Size

Ford et al.[18] of BCR has emphasized the importance of particle size to the effectiveness of limestone utilization. BCR recommended use of minus-325-mesh stone for best results.

Table 9. LIMESTONE NEUTRALIZATION OF ACID MINE DRAINAGE LOGARITHMIC PROBABILITY PLOTS FOR MEAN REACTOR DETENTION TIME

Flow Rate, GPM	Condition in Reactor	Reactor No.	Theoretical Detention Time (Tc)	Mean Probable Logarithmic Detention Time (T)	Mixing Efficiency, Percent (T/To)
15 GPM					
15.1	Standard*	A	6.95 Min.	5.84 Min.	58
15.0	Standard	B	7.00 "	4.76 "	68
14.85	2 Wood Baffles	A	7.07 "	7.00 "	99
14.56	2 Wood Baffles	A	7.21 "	7.07 "	98
14.85	2 Small 400-mesh Screen Baffles	B	7.07 "	5.51 "	78
14.85	2 Large 200-mesh Screen Baffles	A	7.07 "	5.79 "	82
14.85	3 Large 200-mesh Screen Baffles	A	7.07 "	6.29 "	89
14.85	2 Reactors in Series	A	14.48 "	13.68 "	95
10 GPM					
10.2	Standard	A	10.3 Min.	7.62 Min.	74
5 GPM					
5.20	Standard	A	20.2 Min.	16.6 Min.	82
5.00	Standard	B	21.0 "	17.7 "	84
4.90	2 Large 200-mesh Screen Baffles	A	21.4 "	19.5 "	91
5.00	2 Reactors in Series	A	43.0 "	42.9 "	99

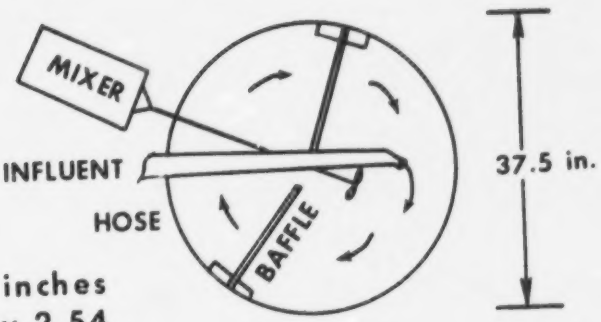
*Standard = No baffles

Note: To convert from gpm to liters/minute, multiply by 3.785.

Table 10. EFFECT OF BAFFLES AT 15 GPM (56.8 LITERS/MIN)

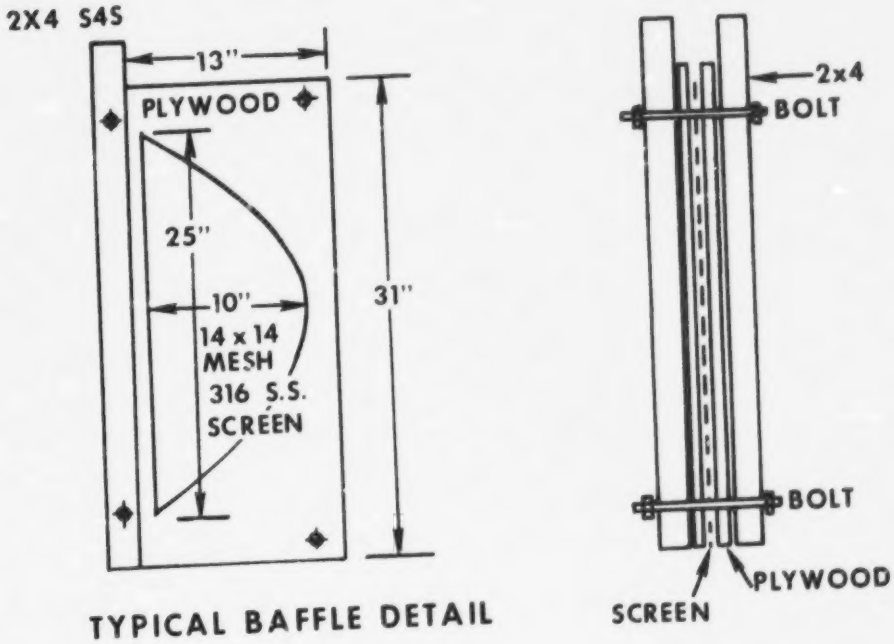
Test Conditions Process A vs. Process B	Process A Limestone Usage, #/1000 Gallons	Process B Limestone Usage, #/1000 Gallons	Percent Reduction in Usage	Was observed difference statistically significant?	Appendix Table Number
Two Wood Baffles vs. no Baffles	7.66	8.54	10.3	No	41
Two Wood Baffles vs. Two Fine Mesh Screen Baffles	5.90	5.55	5.9	Yes	42
Two Large Mesh Screen Baffles vs. Two Small Mesh Screen Baffles	8.34	9.40	11.3	No*	43
Three Large Mesh Screen Baffles vs. Two Large Mesh Screen Baffles	9.42	8.97	4.8	No	44

*Too few samples
Note: To convert from lbs/1000 gal to kg/cu m, multiply by 0.120.



Note: To convert inches to cm, multiply by 2.54.

TOP VIEW
(REACTOR SHOWING INFLUENT HOSE, MIXER, AND BAFFLE LOCATIONS)



TYPICAL BAFFLE DETAIL

Figure 8. Wire-mesh reactor baffle sketch.

To evaluate the use of finely ground limestone on the Grassy Run water, 2000 pounds (907 kg) of rock-dust limestone were ground in a jet mill until 100 percent passed a 325-mesh screen.

A dry sieve test on the finely ground stone was not successful due to static electricity, and the particles would not pass through a 50-mesh screen. To alleviate the problem, the stone was washed through the sieves with cold water. Amounts retained on each screen were dried, weighed, and compared to the original weight of the sample.

For comparison, the wet-wash sieve test was also performed on standard rock-dust limestone.

Results of both tests are presented in Table 11.

Table 11. WET-WASH SIEVE TESTS

Mesh size	Limestone passing through sieve, (percent)	
	Standard rock dust	Jet-milled rock dust
200	76.6	100.0
400	59.9	99.6

Initial batch tests were made to compare the reaction efficiency of the finely ground stone to the regular stone. Both these tests were made using identical 100-gallon (378.5-liter) batches of AMD and a 40-min reaction time for each. Results of these tests are given in Table 12.

Table 12. BATCH SCALE NEUTRALIZATION TEST

	Rock-dust limestone	400-mesh limestone
Date	2/2/71	2/2/71
Volume of water, gal.	100 (378.5 ℓ)	100 (378.5 ℓ)
Reaction time, min.	40	40
Initial pH	2.9	2.9
Final pH	6.5	6.5
Quantity limestone added, grams	643.1	457.7
Utilization efficiency, percent	36.6	51.2
Temperature, °C	6	7

It required 28.8 percent less finely ground limestone (400 mesh) than regular limestone to do the same job.

Following batch-scale testing, the 400-mesh stone was compared to regular limestone under 15 gpm (56.8 1/min), 7-min detention time, continuous-flow conditions. Table 13 shows results of this test. Limestone usage was reduced even further under continuous-flow conditions; 44 percent less 400-mesh limestone was required than regular limestone. Continuous-flow utilization efficiencies of about 80 percent were obtained with the 400-mesh limestone.

Continuous-flow comparisons (Table 14) were then made at a 5 gpm (18.9 1/min) flow rate (21-min detention time). Utilization efficiency averaged better than 90 percent during the test run. These efficiencies were the highest ever recorded for continuous-flow limestone treatment on Grassy Run AMD.

Summaries of chemical analyses for these studies are presented in Table 46 of the Appendix.

BCR has also emphasized that not all limestones are effective in AMD treatment. They characterized the ideal stone as having a large surface area, a high calcium content, and a low impurity level.

A high-calcium, small particle-size limestone (98 percent passing 325-mesh) sample was obtained from the National Gypsum Company, York, Penna., to illustrate BCR's results on the Grassy Run water.

A batch neutralization comparison was made between the York stone and the high-calcium, finely-ground 325-mesh stone (Table 15) used at Norton. The limestone used at Norton was significantly superior in reactivity with AMD, thus indicating, as BCR had observed, that considerably more was involved than particle size.

Table 13. COMPARISON OF 400-MESH LIMESTONE VS. REGULAR LIMESTONE @ 15 GPM (56.8 LITERS/MIN)

Date	Process A 400-Mesh Limestone @ 15 GPM				Process B Regular 'Rock Dust' Limestone @ 15 GPM				
	Effluent pH	Limestone Usage, #/1000 gal.	Utilization Effcy.	Stoichiometric Factor	Effluent pH	Limestone Usage, #/1000 gal.	Utilization Effcy.	Stoichiometric Factor	Percent Reduction in Usage
2/09/71	5.3	3.87	84.0%	1.16	5.1	5.38	59.7%	1.62	28.1
2/10/71	5.0	3.57	89.0%	1.12	5.1	6.95	45.9%	2.12	48.6
2/11/71	5.1	4.10	79.7%	1.23	5.2	7.89	42.1%	2.36	48.0
2/12/71	5.0	4.25	77.0%	1.27	5.2	7.95	41.7%	2.38	46.5
Avg.	5.1	3.95	82.4%	1.20	5.2	7.04	47.4%	2.12	43.9

Note: To convert from lbs/1000 gal to kg/cu m, multiply by 0.120.

CHEMISTRY ANALYSES
EFFLUENT WATER

Date	Process A Iron	Process A Turbidity	Process B Iron	Process B Turbidity
2/09/71	10 mg/l	63 JTU	5 mg/l	81 JTU
2/10/71	10	58	15	79
2/11/71	10	43	15	56
2/12/71	1.8	79	1.3	92

NOTE: Observed difference between Process A and Process B was statistically significant at the 95-percent confidence level.

Table 14. COMPARISON OF 400-MESH LIMESTONE VS. REGULAR LIMESTONE @ 5 GPM (18.9 LITERS/MIN)

Date	Process A 400-Mesh Limestone @ 15 GPM Effluent pH	Limestone Usage, #/1000 gal.	Utilization Effcy.	Stoichiometric Factor	Process B Regular 'Rock Dust' Limestone @ 15 GPM Effluent pH	Limestone Usage, #/1000 gal.	Utilization Effcy.	Stoichiometric Factor	Percent Reduction in Usage
2/24/71 (Temp. 7°C)	5.0	2.72	98.1%	1.00	5.1	5.62	49.6%	2.00	51.6
2/25/71 (Temp. 6°C)	5.1	3.27	90.1%	1.07	5.1	5.32	47.7%	2.07	48.3
2/25/71 (Temp. 14°C)	5.1	3.57	81.9%	1.17	5.0	5.38	55.2%	1.79	33.6
2/26/71 (Temp. 11°C)	5.0	3.24	94.7%	1.02	5.0	5.85	53.9%	1.85	44.6
Averages	5.1	3.20	91.2%	1.07	5.0	5.54	51.6%	1.93	42.2%

Note: To convert from lbs/1000 gal to kg/cu m, multiply by 0.120.

CHEMISTRY ANALYSES

Date	Process A Iron	Process A Turbidity	Process B Iron	Process B Turbidity
2/24/71	6.4 mg/l	45 JTU	3.1 mg/l	45 JTU
2/25/71	5.6	34	5.0	28
2/25/71	5.5	36	7.0	60
2/26/71	6.0	26	4.0	35

NOTE: Observed difference between Process A and Process B was statistically significant at the 95-percent confidence level.

Table 15. COMPARISON OF FINELY-GROUND GERMANY VALLEY LIMESTONE AND FINE-MESH LIMESTONE FROM YORK, PENNSYLVANIA

	Germany Valley stone (325-mesh)	York, Pa. stone (325-mesh)
Raw water pH	3.0	3.0
Raw water temperature, °C	7	13
Amount of water, gallons	100 (378.5 liters)	100 (378.5 ltr)
Amount of limestone required, gpm	243.4	464.9
Effluent pH	6.5	6.5
Reaction time, minutes	40	40
Utilization efficiency, percent	76.2	39.2
Percent passing 325-mesh	100.0	99.8

Effect of Dry Feed vs. Slurry Feed

Previous studies by EPA[5] indicated that slurry feeding had no advantage over dry feeding. The use of a slurry feed system with wire-mesh baffles in the slurry mix tank was suggested, however, since smaller particles of limestone might be produced from abrasion against the wire mesh.

Three series of batch studies were conducted to test this hypothesis. Limestone slurry was prepared by adding 40 pounds (18.1 kg) of limestone to 100 gallons (378.5 liters) of water in a slurry tank equipped with two wire-mesh baffles and a flash mixer. Since the tank inevitably had dead spots in it, the slurry could not be assumed to be uniform. Aliquots of the slurry were used to neutralize the AMD. In order to determine the quantity of limestone actually added, duplicate amounts of slurry were taken. The first portion of slurry was added to the AMD in the reaction tank; the duplicate was filtered, dried, and weighed.

A comparison of the effectiveness of dry feeding vs. slurry feeding is presented in Table 16. In the first test, slurry feeding was more efficient. In the second series, slurry feeding was only slightly more efficient. In the final tests, dry feeding was more efficient.

Thus, no significant difference was observed between dry and slurry feeding, but dry feeding is more desirable because of its simplicity.

These studies may clarify the role of the wire-mesh baffles in neutralization reaction. If the baffles do decrease particle size, then slurry feeding should have been significantly superior to dry feeding because of the limestone's extended exposure to the screens in the slurry mix tank. Since it wasn't, the baffles must have little effect upon particle size.

Effect of Two-Step Limestone Treatment

A feasibility test was made to determine if any advantage would be obtained by adding limestone to the AMD in two separate steps. Four identical 125-gallon (473-liter) batches of AMD were used for the study. Each received a total of 600 grams of limestone. Reaction time for all tests was 40 minutes.

Table 16. LIMESTONE SLURRY VS. DRY FEED NEUTRALIZATION STUDY BATCH SCALE TESTS

Date	Type of Limestone Used	Initial pH	Amount of Limestone Required	Final pH	Amt. of Water	Reaction Time	Effi-ciency	Temp. °C
12/30/70	Dry Rock Dust	2.9	578.2 Grams	6.2	100 Gal.	40 Mins.	48.5%	7
12/30/70	Slurried Rock Dust	2.9	465.8 (11000 ml of slurry)	6.3	100 Gal.	40 Mins.	61.0%	7
12/30/70	Slurried Crusher Dust	2.9	540.8 (11000 ml of slurry)	6.3	100 Gal.	40 Mins.	51.8%	7
1/19/71	Dry Rock Dust	3.1	682.7 Grams	6.5	100 Gal.	40 Mins.	32.1%	4
1/19/71	Slurried Rock Dust	3.1	684.1 Grams (14000 mls of slurry)	6.5	100 Gal.	40 Mins.	32.7%	4
1/29/71	Dry Rock Dust	2.9	637.6 Grams	6.7	100 Gal.	40 Mins.	38.0%	10
1/29/71	Slurried Rock Dust	2.9	750.1 Grams (8000 mls of slurry)	6.7	100 Gal.	40 Mins.	32.3%	10

Slurries were made by adding 40 lbs. of limestone to 100 gal. of tap water in a reactor with wire mesh baffles in it.

Note: To convert from gallons to liters, multiply by 3.785; to convert from pounds to kg, multiply by 0.454.

In Test No. 1, the entire quantity of limestone was added initially and the pH was recorded every 5 minutes. Half of the limestone was added initially in Test No. 2, and the remaining half was added after 20 minutes. In Test No. 3, 75 percent was added initially, and the remaining 25 percent was added after 20 minutes. Test No. 4 was the same as Test No. 1 to check the reproducibility of results.

Results of the study (Table 17) indicate that there is no advantage to two-step treatment. In fact, it was more advantageous to add all the limestone initially due to the more rapid and complete reaction at lower pH's. The limestone added in this study was 2.76 times the stoichiometric requirement.

Simulated Sludge-Recycling Tests

Unfortunately, the Norton facility did not have the capability to continuously withdraw and recycle sludge. To investigate the feasibility of sludge recycling, it was necessary to store the sludge in a reservoir and use this to simulate continuous withdrawal conditions.

All tests were done on a batch basis. As shown in Table 18, no sludge was added to the first test. Sludge was added to the following tests in progressively larger quantities. For the final test, the sludge that had precipitated from Test No. 4's neutralization was used.

Table 18. SIMULATED SLUDGE-RECYCLING TESTS

Test No.	Initial pH	Quantity of sludge added, (gal)[a]	pH 5-min after sludge addition	Amount of limestone added, (grams)	Final pH
1	2.9	0	-	500.0	6.8
2	2.9	2	4.8	289.2	6.8
3	2.9	4	5.2	155.4	6.8
4	2.9	8	5.8	54.2	6.8
5[b]	2.9	12.5	5.6	325.0	6.8

A 100-gal (378.5-liter) batch of AMD was used for each test. Total reaction time for each test was 40 minutes. The majority of the limestone was added 5 minutes after sludge addition.

[a]To convert gallons to liters, multiply by 3.785.

[b]The sludge resulting from the Test No. 4 neutralization was used for Test No. 5.

Table 17. LIMESTONE SPLIT TREATMENT FEASIBILITY STUDY

Time	TEST NO. 1		TEST NO. 2		TEST NO. 3		TEST NO. 4	
	Limestone Added Grams	pH	Limestone Added Grams	pH	Limestone Added Grams	pH	Limestone Added Grams	pH
0	600	2.9	300	2.9	450	2.9	600	2.9
5 Min.		5.70		4.90		5.50		5.70
10 Min.		6.00		5.10		5.80		6.00
15 Min.		6.18		5.30		6.00		6.20
20 Min.		6.30	300	5.40	150	6.18		6.35
25 Min.		6.38		6.15		6.30		6.40
30 Min.		6.45		6.25		6.38		6.45
35 Min.		6.50		6.38		6.42		6.50
40 Min.		6.50		6.45		6.50		6.50

Note: In each test, quantities of limestone were added at various intervals to a reaction chamber containing 125 gallons of acid mine drainage and stirred vigorously for the specified time as indicated. (125 gal = 473 liters).

As more sludge was added, less limestone was required (until Test No. 5). The increased limestone requirement of Test No. 5 is more representative of continuous-flow recycling as Test 4's neutralization did not supply as much alkalinity in 12.5 gallons (47.3 liters) of sludge as was available in 2 gallons (7.6 liters) of the original sludge. This conclusion is confirmed by the chemical analyses shown in Table 19.

The original sludge was significantly higher in percent solids, alkalinity, and calcium than were the sludges from Tests 1 through 5. Sludge iron and sulfate were not dramatically affected by the recycling.

Increasing the amount of recycled sludge increased the effluent sulfate content. In Test No. 5, for example, the effluent was near saturation for calcium sulfate. No chemical parameters other than sulfate were adversely affected by sludge addition.

Conclusions drawn from these tests were:

1. Sludge recycling should increase reaction efficiency and sludge solids content, though not to the extreme extent shown in these tests.
2. With the exception of increased sulfate content, product water quality was not degraded by sludge recycling.
3. Partial utilization of the large residual alkalinity in the sludge can be accomplished by recycling.

Following the batch-scale study, a continuous-flow test was attempted. Small electrical oscillating pumps were used to transfer sludge from the settling pool back into the reaction chamber. The recycle flow rate was regulated by throttling the discharge from the pumps to attain a 1 gpm (3.8 l/min) flow rate. A 10:1 AMD to recycled-sludge ratio was used. Results of the continuous-flow study are presented in Table 20. A summary of chemical analyses for this study is presented in Table 46 of the Appendix.

The steady decrease in efficiency in Process B was attributed to the failure of the sludge pool to achieve equilibrium conditions. Every

Table 19. CHEMISTRY ANALYSES FOR SIMULATED SLUDGE RECYCLE BATCH TESTS

Sample Designation	pH	Alkalinity	Cond. Mmhos/cm	Acidity	Calcium	Mg.	Iron	Al.	SO_4	Sludge Added, Percent by Vol.	Reaction Efficiency, Percent
Raw Feed	2.8	--	1300	471	110	36	132	44	655		
Supernatant #1	6.2	29	1180	4	300	35	2.5	2.0	696	0	37.7
Supernatant #2	6.2	35	1220	4	340	36	2.0	2.0	655	2	66.1
Supernatant #3	6.6	29	1200	4	360	36	1.0	2.0	819	4	121.5
Supernatant #4	6.5	33	1200	4	400	38	1.0	2.0	955	8	351.2
Supernatant #5	6.5	35	1200	3	365	36	3.0	2.0	1470	12.5	58.8*
	Percent Solids										
Sludge	21.0	65,000			5200		4300		2500		
Sludge #1	5.72	22,000			2500		3800		2200		
Sludge #2	12.30	20,000			1500		4300		3000		
Sludge #3	14.10	20,000			1400		4200		2900		
Sludge #4	15.85	27,500			2300		3600		2900		
Sludge #5	15.76	32,500			3000		4000		2900		

*Sludge added to Test No. 5 was left from Test No. 4's neutralization.

NOTE: Test data taken December 10-11, 1970.
All units expressed as mg/l unless otherwise noted.

Table 20. COMPARISON OF SLUDGE RECIRCULATION VS NO RECIRCULATION @ 10 GPM (37.9 LITERS/MIN)

	Process A - No Sludge Recirculation 10 GPM Flow (Raw Water)				Process B - Recirculating 1 GPM of Sludge 10 GPM Flow (Raw Water)			
Date	Effluent pH	Limestone Usage, #/1000 gal.	Utilization Effcy.	Stoichiometric Factor	Effluent pH	Limestone Usage, #/1000 gal.	Utilization Effcy.	Stoichiometric Factor
3/31/71	5.0	5.674	52.0%	1.88	5.1	2.426	113.1%	0.88
4/01/71	5.0	6.696	48.2%	2.06	5.1	1.799	179.5%	0.55
4/02/71	5.0	6.784	50.1%	1.94	5.1	3.814	90.8%	1.09
4/03/71	5.0	6.246	55.0%	1.78	5.2	4.859	70.9%	1.39

Sludge Volume After One Hour:
Process A = 1.0 Percent
Process B = 3.8 Percent
Note: To convert from lbs/1000 gal to kg/cu m, multiply by 0.120.

EFFLUENT WATER

	Process A		Process B	
Date	Iron	Turbidity	Iron	Turbidity
3/31/71	2.2 mg/l	63 JTU	7 mg/l	85 JTU
4/01/71	10	61	18	98
4/02/71	2	28	2	34
4/03/71	5	57	2	58

NOTE: Observed difference between Process A and Process B was statistically significant at the 95-percent confidence level.

attempt was made to move the recycle pump inlets as often as possible to provide representative sludge for recycling, but this was obviously not an ideal mechanism for continuous removal. Basically, the results of the continuous-flow study served to reinforce the findings of batch scale studies; i.e., that recycling does have potential for improving limestone utilization. Further studies are in order on equipment more suited to the task.

Comparison of Limestone Utilization Efficiencies from Various Continuous-Flow Tests

At this point, the major variables that could be studied at Norton had been investigated. The important parameters in the limestone reaction had been characterized, and those that could be controlled were reaction time (20 minutes or more), particle size (rock dust most feasible economically), baffle configuration (two 14-mesh wire screen baffles), and effluent pH (the minimum possible to meet water quality discharge standards). Table 21 presents a summary of the limestone utilization efficiencies observed for the various continuous-flow tests. At pH 5.0, an increase in efficiency of 14 percentage points was observed between the most efficient and least efficient studies.

Table 21. SUMMARY OF LIMESTONE UTILIZATION EFFICIENCIES FROM CONTINUOUS FLOW TESTS

Test Condition	Efficiencies, percent	
	Observed	Mean
pH 5.0		
15-gpm (56.8 liter/min) flow rate	46, 47, 47, 52	48
10-gpm (37.9 liter/min) flow rate	51	51
5-gpm (18.9 liter/min) flow rate	55	55
Two reactors in series @ 15 gpm	59	59
Two wooden baffles @ 15 gpm	55, 56	56
Two small-mesh screen baffles @ 15 gpm	55, 58	57
Two large-mesh screen baffles @ 15 gpm	55, 60	58
Two reactors in series with large-mesh baffles @ 5 gpm	62	62
pH 6.5		
Two large-mesh baffles @ 5 gpm	40, 60	50
Two large-mesh baffles @ 10 gpm	36, 47	42

LIMESTONE VS LIME

After defining the important parameters in the limestone reaction, it was time to test the optimized limestone configuration against its competitor, hydrated lime. Two continuous-flow studies were made: one at 10 gpm (37.9 l/min) at pH 6.4, and one at 5 gpm (18.9 l/min) at pH 6.5. Results of these tests are given in Tables 22 and 23. Chemical analyses summaries are presented in Table 46 of the Appendix. The comparison was necessarily evaluated on the basis of cost, using lime raw-material cost of 0.90 cents/lb and 0.30 cents/lb for limestone. At 10 gpm (37.9 l/min), lime was 36 percent cheaper than limestone for the cost of reagent usage. However, at 5 gpm (18.9 l/min), the costs were closer, with lime only 20 percent cheaper than limestone. The improved sludge solids content of limestone (15.6 vs 2.6 percent) could possibly more than compensate for the initial cost advantage of lime.

Raising the treatment pH to 6.5 (as opposed to the optimization test pH of 5.0) decreased utilization efficiencies of limestone from approximately 60 percent at pH 5 to 40 percent at pH 6.5 and 5 gpm (18.9 liter/min). An example of 10-gpm (37.9 l/min) efficiencies obtained using limestone at pH's above 6 is given in Table 24 along with the chemical analyses.

COMBINATION LIMESTONE-LIME TREATMENT[26]

Limestone treatment offered several advantages over lime treatment; namely, higher density -- lower volume sludges, cheaper raw materials, easier handling of materials because of the less toxic nature of limestone, and freedom from the pollution potentials of accidental overtreatment. Conversely, the biggest disadvantage to limestone was its relatively inefficient reaction rate, which in most cases caused lime to be more economical. Limestone was also unable to produce pH's in excess of 7.0, which are necessary for rapid ferrous iron oxidation.

In most cases, limestone treatment could effectively compete with lime only on ferric iron waters or waters in which the iron could be cheaply oxidized to ferric before neutralization (such as by biological oxidation).

Table 22. LIMESTONE VS LIME @ 10 GPM (37.9 LITERS/MIN)

Date	Process A - Limestone @ 10 gpm			Process B - Lime @ 10 gpm			
	#/1000 gal. Limestone	Final pH	Cost Limestone/ 1000 gal.	#/1000 gal. Lime	Final pH	Cost Lime/ 1000 gal.	Material Cost Reduction
10/19/71	19.470	6.4	5.841¢	4.440	6.4	3.996¢	31.6%
10/21/71	22.845	6.4	6.854¢	4.866	6.4	4.379¢	36.1%
10/27/71	13.599	6.3	4.080¢	3.160	6.3	2.844¢	30.3%
10/28/71	18.839	6.4	5.652¢	3.536	6.3	3.182¢	43.7%
10/29/71	18.575	6.4	5.573¢	3.865	6.4	3.479¢	41.1%
Mean	18.666	6.4	5.600¢	3.973	6.4	3.576¢	36.1%
	Percent Solids (Sludge) 15.6%			Percent Solids (Sludge) 2.6%			

Typical Utilization Efficiencies
Process A = 35.5% Process B = 100%

Raw Material Costs:

Limestone: 0.30¢/lb @ $ 6.00/ton
Lime : 0.90¢/lb @ $18.00/ton

Date	Process A		Process B	
	Effluent Iron	Effluent Turbidity	Effluent Iron	Effluent Turbidity
10/19/71	2.2 mg/l	13 JTU	1.5 mg/l	6 JTU
10/21/71	2.0	11	3.0	6
10/27/71	1.4	12	1.6	8
10/28/71		12	-	
10/29/71	2.6	10	1.4	5

NOTE: Observed difference between Process A and Process B was statistically significant at the 95-percent confidence level. To convert from lbs/1000 gal to kg/cu m, multiply by 0.120. To convert from cents/1000 gal to cents/cu m, multiply by 0.264.

Table 23. LIMESTONE VS LIME @ 5 GPM (18.9 LITERS/MIN)

	Process A - Limestone @ 5 gpm			Process B - Lime @ 5 gpm			
Date	#/1000 gal. Limestone	Final pH	Cost Limestone/ 1000 gal.	#/1000 gal. Lime	Final pH	Cost Lime/ 1000 gal.	Material Cost Reduction
11/16/71	15.851	6.6	4.755¢	4.675	6.6	4.208¢	11.5%
11/17/71	16.282	6.6	4.885¢	4.610	6.6	4.149¢	15.1%
11/18/71	15.471	6.5	4.641¢	4.426	6.5	3.983¢	14.2%
11/19/71	15.603	6.5	4.681¢	4.382	6.5	3.944¢	15.7%
11/20/71	17.796	6.5	5.339¢	4.076	6.3	3.668¢	31.3%
11/21/71	16.241	6.5	4.872¢	3.658	6.4	3.292¢	32.4%
Mean	16.207	6.5	4.862¢	4.305	6.5	3.875¢	20.3%

Typical Utilization Efficiencies
Process A = 39.5% Process B = 100%

Raw Material Costs:
Limestone: 0.30¢/lb. @ $ 6.00/ton
Lime: 0.90¢/lb. @ $18.00/ton

	Process A		Process B	
Date	Effluent Iron	Effluent Turbidity	Effluent Iron	Effluent Turbidity
11/16/71	.5 mg/l	11 JTU	1.7 mg/l	5 JTU
11/17/71	1.5	8	1.4	4
11/18/71	.2	8	2.6	4
11/19/71	.7	10	.6	4
11/20/71	1.3	13	.8	5
11/21/71	.9	19	1.2	6

NOTE: Observed difference between Process A and Process B was statistically significant at the 95-percent confidence level. To convert from cents/1000 gal to cents/cu m, multiply by 0.264. To convert from lbs/1000 gal to kg/cu m, multiply by 0.120.

Table 24-A. HIGH pH LIMESTONE RUN @ 10 GPM (18.9 LITERS/MIN)

Date	Effluent pH	Limestone Requirement, #/1000 Gal.	Stoichiometric Factor	Utilization Efficiency	Effluent Iron	Effluent Turbidity	Process
4/13/71	6.2	13.181	2.92	37.5%	1.6	50	B
4/13/71	6.2	12.874	2.86	37.4%	1.1	58	A
4/14/71	6.5	11.913	3.01	36.4%	2.3	55	A
4/15/71	6.4	13.183	3.36	32.4%	4.5	58	A
4/16/71	6.4	14.019	3.36	33.8%	4.6	54	A

Note: To convert from lbs/1000 gal to kg/cu m, multiply by 0.120.

Table 24-B. CHEMICAL ANALYSES FOR THE HIGH pH LIMESTONE STUDY

Sample	pH at Time of Analysis	Acidity as $CaCO_3$	Cond.	Ca	Mg	Al	Total Iron	Sulfate	Alkalinity	Turbidity	pH When Sample Was Taken
Raw Feed	2.7	490	1180	96	31	32	88	700	--	--	2.7
Pools A & B	6.3	3.0	920	2450	250	1.1	3.1	570	62	55	6.3

All units are mg/l except for turbidity (JTU), conductivity (micromhos/cm) and pH.

In an effort to cover a broader spectrum of application, the logical extension of the research was to combine the limestone and lime processes. Since limestone was cheap and highly reactive at low pH's (less than 5), as shown in Figure 2, it could be added first to the AMD. Lime, being more expensive but highly reactive to pH 9 and above, might be used to "polish" the water previously treated with limestone. In this manner, combination treatment should enable both limestone and lime to be used in their respective most efficient ranges of reactivity. Utilization of limestone's lower raw-material cost should therefore result in an overall cost reduction of the combination as compared to either reagent alone. An improvement in sludge characteristics should also result from the use of limestone. Use of the lime should enable the application of the technique to all ferrous iron situations where a high pH would be required for rapid, efficient iron oxidation.

Batch Scale Tests

Investigation of combination limestone-lime treatment began with a series of neutralization studies made on 125-gallon (473-liter) batches of Grassy Run water. The neutralization reactor was equipped with a flash mixer and two 14-mesh wire screen baffles. Use of a 1500-gallon (5680 liter) storage reservoir insured consistent water quality for all tests.

In each test, the AMD was neutralized to pH 6.5. One test was made using limestone alone to neutralize to pH 6.5; and another used lime alone, the rest of the tests used limestone first to neutralize to a given pH (3.5, 4.0, 4.5, 5.0, 5.5, and 6.0) and then added lime to increase the pH to 6.5. Reaction time for each neutralizing agent was 20 minutes. Where combination treatment was tested, 20 minutes were allowed for the limestone reaction and an additional 20 minutes for lime. Since limestone and lime involve independent reactions that must take place in that respective order, the reaction times used simulated a 5-gpm (18.9 l/min) flow rate through the Norton pilot plant.

Results of these tests are shown in Table 25 and Figure 9. Reagent cost was the important parameter under consideration. Combination

Table 25. LIMESTONE-LIME BATCH SCALE STUDY

Initial Limestone pH	Amt. Limestone Required, lbs/1000 gal.	Cost of Limestone /1000 gal, Cents	Final pH	Amt. Lime Required, lbs/1000 gal.	Cost of Lime per 1000 gal, Cents	Total Cost, Cents per 1000 gal.	Total Neutralizer Added, mg/l	Stoichiometric Factor
3.5	3.784	1.135	6.5	1.549	1.394	2.529	705.64	1.17
4.0	4.215	1.265	6.5	1.331	1.198	2.463	721.93	1.19
4.5	4.905	1.472	6.5	1.118	1.006	2.590	770.34	1.27
4.7	6.160	1.848	6.5	0.672	0.605	2.453	848.98	1.40
5.0	6.885	2.067	6.5	0.304	0.274	2.341	876.46	1.45
5.5	8.483	2.545	6.5	0.118	0.106	2.651	1038.19	1.72
6.0	9.654	2.896	6.8	0.016	0.014	2.910	1162.07	1.92
6.5	11.644	3.493	6.5	All limestone	All limestone	3.493	1398.62	2.31
	All lime		6.5	3.379	3.041	3.041	547.95	0.91

Reaction Time = 20 minutes Limestone
20 minutes Lime

Reactor Capacity = 125 gallons (473 ltr) Lime costs 0.90 cents/lb; Limestone costs 0.3 cents/lb

Note: To convert from lbs/1000 gal to kg/cu m, multiply by 0.120. To convert from cents/1000 gal to cents/cu m, multiply by 0.264.

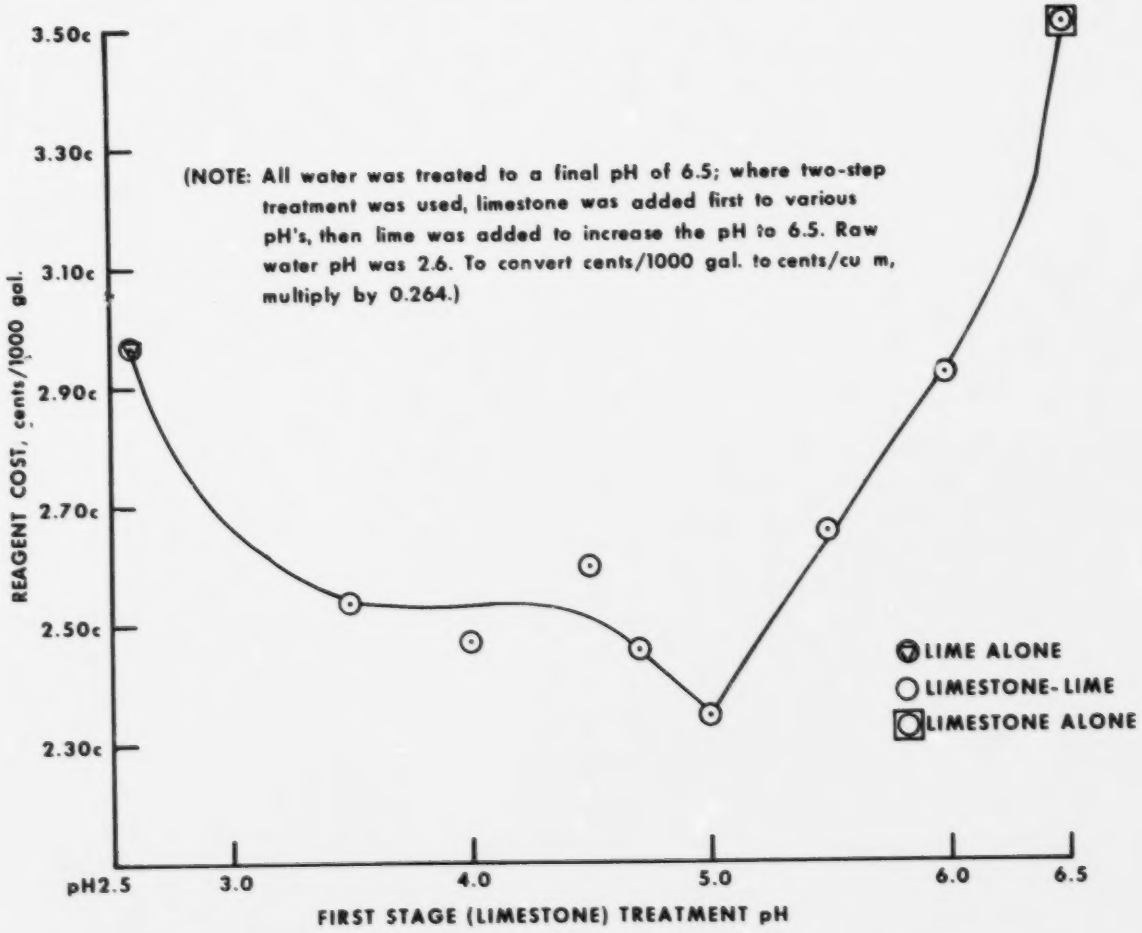


Figure 9. Cost of various combinations in two-stage limestone/lime treatment schemes.

treatment to limestone (first stage) pH 5.0 proved to be the most economical. This combination was 33 percent cheaper than limestone alone and 23 percent cheaper than lime alone. As seen in Figure 9, virtually all combinations of two-stage treatment were more economical than either lime or limestone alone.

Continuous-Flow Tests

The success of the batch scale tests led directly into continuous-flow testing of the combination process. For the pilot testing, Process A consisted of two reactors in series. Limestone was continuously added to the first reactor to partially neutralize the AMD. The partially neutralized water was then pumped to a second reactor where lime was added. Control of the pH of the first reactor effluent was accomplished by manually adjusting a variable speed drive on the limestone dry feeder. Lime addition to the second reactor was controlled automatically by a pH controller to maintain a desired pH in the clarifier.

Process B consisted of a single reactor also equipped with two wire-mesh baffles. Neutralizer addition to Process B was controlled automatically by clarifier effluent pH.

Combination limestone-lime treatment was first tested against limestone treatment to pH 6.5 at flow rates of 5 and 10 gpm (18.9 and 37.9 l/min) and then against lime treatment to pH 6.5, also at 5 and 10 gpm.

Slight differences were observed when batch-scale results were expanded to pilot scale. A first-step (limestone) pH of 5.0, which was optimum in batch studies, required virtually no second-stage (lime) treatment in the pilot plant to reach a clarifier effluent pH of 6.5. This difference was attributed to the longer detention time provided by the pilot plant clarifier. Lowering the first-stage pilot plant pH near 4 produced results comparable to the batch scale studies at a first-stage pH of 5.

Tables 26 and 27 present the physical and cost data for combination limestone-lime treatment versus limestone treatment at 5 and 10 gpm

Table 26. LIMESTONE-LIME VS LIMESTONE @ 5 GPM (18.9 LITERS/MIN)

Date	Process A - Combination Limestone & Lime @ 5 gpm							Process B - Limestone			
	#/1000 Gal. Limestone	Lime-stone pH	#/1000 Gal. Lime	Final pH	Cost per 1000 Gal.* Lime-stone, Cents	Lime, Cents	Total, Cents	#/1000 Gal. Limestone	Final pH	Cost* /1000 Gal. Cents	Material Cost Re-duction
8/17/71	5.453	4.7	.849	6.7	1.636	.764	2.400	10.550	6.6	3.165	24.2%
9/21/71	2.569	4.5	.973	6.4	.771	.876	1.647	6.749	6.4	2.025	18.7%
9/29/71	3.955	3.8	1.253	6.4	1.187	1.128	2.315	10.078	6.4	3.023	23.4%
9/30/71	4.348	4.1	1.339	6.4	1.304	1.205	2.509	12.125	6.4	3.638	31.0%
10/1/71	3.867	3.9	1.388	6.4	1.160	1.249	2.409	12.455	6.4	3.737	35.5%
10/2/71	4.495	4.4	1.252	6.4	1.349	1.127	2.476	10.936	6.5	3.281	24.5%
10/5/71	5.905	4.2	1.562	6.4	1.772	1.406	3.178	16.234	6.5	4.870	34.7%
Average	4.370	4.2	1.231	6.4	1.311	1.108	2.419	11.304	6.5	3.391	28.7%

*Chemical cost only.

Raw Material Costs:
Limestone = 0.30 cents/lb. @ $ 6.00/ton
Lime = 0.90 cents/lb. @ $18.00/ton

NOTE: Observed difference between Process A and Process B was statistically significant at the 95-percent confidence level. To convert from lbs/1000 gal to kg/cu m, multiply by 0.120. To convert from cents/1000 gal to cents/cu m, multiply by 0.264.

Table 27. LIMESTONE-LIME VS LIMESTONE @ 10 GPM (37.9 LITERS/MIN)

Date	Process A - Combination Limestone & Lime @ 10 gpm							Process B - Limestone @ 10 gpm			
	#/1000 Gallons Limestone	Lime-stone pH	#/1000 Gallons Lime	Final pH	Cost /1000 Gal. Lime-stone, Cents	Lime, Cents	Total, Cents	#/1000 Gallons Limestone	Final pH	Cost /1000 Gal. Cents	Material Cost Re-ductions Percent
6/15/71	5.153	4.3	0.110	6.1	1.546	0.099	1.645	10.524	6.2	3.157	47.9
6/17/71	4.120	3.7	1.68	6.7	1.236	1.512	2.748	12.44	6.5	3.732	26.4
6/18/71	3.967	3.65	1.643	6.5	1.190	1.479	2.669	12.80	6.5	3.840	30.5
6/24/71	5.556	4.5	0.648	6.5	1.667	.583	2.250	10.846	6.4	3.254	30.9
Average	4.699	4.0	1.020	6.5	1.410	.918	2.328	11.653	6.4	3.496	33.4

Raw Material Costs:
Limestone = 0.30 cents/lb. @ $ 6.00/ton
Lime = 0.90 cents/lb. @ $18.00/ton

NOTE: Observed difference between Process A and Process B was statistically significant at the 95-percent confidence level. To convert from lbs/1000 gal to kg/cu m, multiply by 0.120. To convert from cents/1000 gal to cents/cu m, multiply by 0.264.

respectively (18.9 and 37.9 1/min). Chemical analyses for all pilot plant studies are presented in Table 28.

For combination treatment versus lime treatment, the physical and cost data are given in Tables 29 and 30.

Reducing Material Cost

An overall summary of the effectiveness of combination treatment in reducing material costs is given in Table 31, which shows that increasing the reaction time had very little effect on the cost advantage of the combination treatment as compared to lime treatment alone (25.2 vs. 25.7 percent). In the case of limestone, however, the difference in reaction time was significant (33.4 vs. 28.7 percent), as the limestone reaction is strongly time dependent. Increasing reaction time significantly increased limestone utilization efficiency and, in the above case, was obviously a greater benefit to the limestone reaction than to the combination process, since a reduction in cost advantage occurred at the lower flow rate.

Table 31. MATERIAL COST ADVANTAGE OF COMBINATION TREATMENT

Combination treatment as compared to:	Cost advantage of combination, percent	
	Flow: 10 gpm (37.9 1/min)[a]	5 gpm (18.9 1/min)[b]
Lime	25.2	25.7
Limestone	33.4	28.7

[a]Reaction time @ 10 gpm, 9.1 min.

[b]Reaction time @ 5 gpm, 19.1 min.

Effluent Quality

No advantage of one process over another was observed in terms of effluent water quality (Table 28). As expected, all three processes produced effluents of similar quality since the solubilities of such elements as iron and aluminum were more critically responsive to pH than to any other parameter.

Table 28. CHEMISTRY ANALYSES: PILOT PLANT STUDIES

	pH	Alk. as $CaCO_3$	Cond. Mmhos/cm	Acidity as $CaCO_3$	Ca	Mg	Total Iron	Al.	SO_4	Turbidity, JTU
5 GPM										
Raw Feed (Grassy Run)	2.7	0	1580	560	120	45	130	43	930	-
Limestone-Lime Effluent	6.4	16	1320	0	360	38	0.8	2	850	9
Limestone Effluent	6.5	18	1350	0	360	45	1.4	3	830	12
10 GPM										
Raw Feed (Grassy Run)	2.5	0	2240	600	130	44	110	69	650	-
Limestone-Lime Effluent	6.5	20	1570	0	350	42	1.8	1	760	15
Limestone Effluent	6.4	55	1640	0	370	46	1.6	1	740	18
5 GPM										
Raw Feed (Grassy Run)	2.7	0	1900	570	135	46	120	41	630	-
Limestone-Lime Effluent	6.4	15	1520	2	340	47	0.6	1	630	3
Lime Effluent	6.3	10	1520	1	350	41	0.5	1	650	5
10 GPM										
Raw Feed (Grassy Run)	2.8	0	1480	370	170	120	32	23	480	-
Limestone-Lime Effluent	6.5	18	1150	1	200	120	1.0	2	380	8
Lime Effluent	6.5	10	1150	1	200	120	1.0	2	410	3

NOTE: All units expressed as mg/l unless otherwise noted. To convert from gpm to liters/minute, multiply by 3.785.

Table 29. LIMESTONE-LIME VS LIME @ 5 GPM (18.9 LITERS/MIN)

Date	Process A - Combination Limestone & Lime @ 5 gpm							Process B - Lime @ 5 gpm			
	#/1000 Gallons Limestone	Lime-stone pH	#/1000 Gallons Lime	Final pH	Cost per 1000 Gal. Lime-stone, Cents	Lime, Cents	Total, Cents	#/1000 Gallons Lime	Final pH	Cost /1000 Gal, Cents	Material Cost Reduction, Percent
7/24/71	3.345	3.6	1.352	6.2	1.004	1.217	2.221	3.462	6.2	3.116	28.7
7/25/71	4.447	4.3	1.308	6.5	1.334	1.177	2.511	3.408	6.3	3.067	18.1
7/29/71	4.297	4.1	1.349	6.2	1.289	1.214	2.503	3.914	6.2	3.523	29.0
7/30/71	4.093	3.8	1.393	6.5	1.228	1.254	2.482	3.751	6.3	3.376	26.5
Average	4.046	4.0	1.351	6.4	1.214	1.216	2.430	3.634	6.3	3.271	25.7

Raw Material Costs:
Limestone = 0.30 cents/lb. @ $ 6.00/ton
Lime = 0.90 cents/lb. @ $18.00/ton

NOTE: Observed difference between Process A and Process B was statistically significant at the 95-percent confidence level. To convert from lbs/1000 gal to kg/cu m, multiply by 0.120. To convert from cents/1000 gal to cents/cu m, multiply by 0.264.

Table 30. LIMESTONE & LIME VS LIME @ 10 GPM (37.9 LITERS/MIN)

Date	Process A - Combination Limestone & Lime @ 10 gpm							Process B - Lime @ 10 gpm			
	#/1000 Gallons Limestone	Limestone pH	#/1000 Gallons Lime	Final pH	Cost per 1000 Gal. Limestone, Cents	Lime, Cents	Total, Cents	#1000 Gallons Lime	Final pH	Cost /1000 Gal, Cents	Material Cost Reduction, Percent
8/5/71	1.213	4.2	.283	6.5	.364	.255	.619	1.116	6.5	1.004	38.3
8/6/71	.980	3.6	.479	6.5	.294	.431	.725	1.181	6.5	1.063	31.8
8/7/71	2.728	4.8	.303	6.5	.818	.273	1.091	2.133	6.6	1.920	43.2
8/8/71	4.062	4.5	.656	6.5	1.219	.626	1.845	2.269	6.5	2.042	9.6
8/9/71	2.609	4.3	1.161	6.5	.783	1.045	1.828	3.006	6.3	2.705	32.4
8/10/71	4.851	4.4	1.295	6.3	1.455	1.166	2.621	3.269	6.5	2.942	10.9
Average	2.741	4.3	.703	6.5	.822	.633	1.455	2.162	6.5	1.946	25.2

Raw Material Costs:
Limestone = 0.30 cents/lb @ $ 6.00/ton
Lime = 0.90 cents/lb @ $18.00/ton

NOTE: Observed difference between Process A and Process B was statistically significant at the 95-percent confidence level. To convert from lbs/1000 gal to kg/cu m, multiply by 0.120. To convert from cents/1000 gal to cents/cu m, multiply by 0.264.

Sludge Characteristics

It was difficult to determine sludge settling rates, since a definite supernatant/sludge interface never clearly developed during settling. Instead of attempting to estimate the position of the interface, it was decided to measure supernatant turbidity as a function of time. Sludge from all three processes was allowed to settle undisturbed in 1000-ml graduates, and supernatant turbidity was measured periodically. It was also possible to read the sludge buildup in the bottom of the graduates, even though the settling interface never developed. Figure 10 presents graphs of both sets of data. Water treated with lime clarified most rapidly, followed closely by limestone-lime and limestone treatment. All three supernatants achieved similar clarity at the end of 1 hour.

Sludge produced by lime was the most voluminous of the three and compacted gradually. Limestone and limestone-lime treatment produced significantly smaller volumes of sludge than did lime treatment. After 2 hours of settling, lime sludge occupied 10 percent of its original volume, while limestone and limestone-lime occupied less than 4 percent of their initial volumes.

Sludge samples taken during the individual pilot-plant test runs were analyzed to determine the percent solids; results are presented in Table 32.

Table 32. COMPARISON OF SLUDGE PERCENT SOLIDS

Flow rate, gpm	Sludge solids, percent			Theoretical settling time, hr
	Treatment method			
	Limestone-lime	Lime	Limestone	
5 (18.9 l/min)	10.7	2.3	13.4	39
10 (37.9 l/min)	6.0	1.4	15.6	19.5

Longer detention time, which significantly increased sludge percent solids for limestone-lime and for lime sludges, had little comparative effect on limestone sludge.

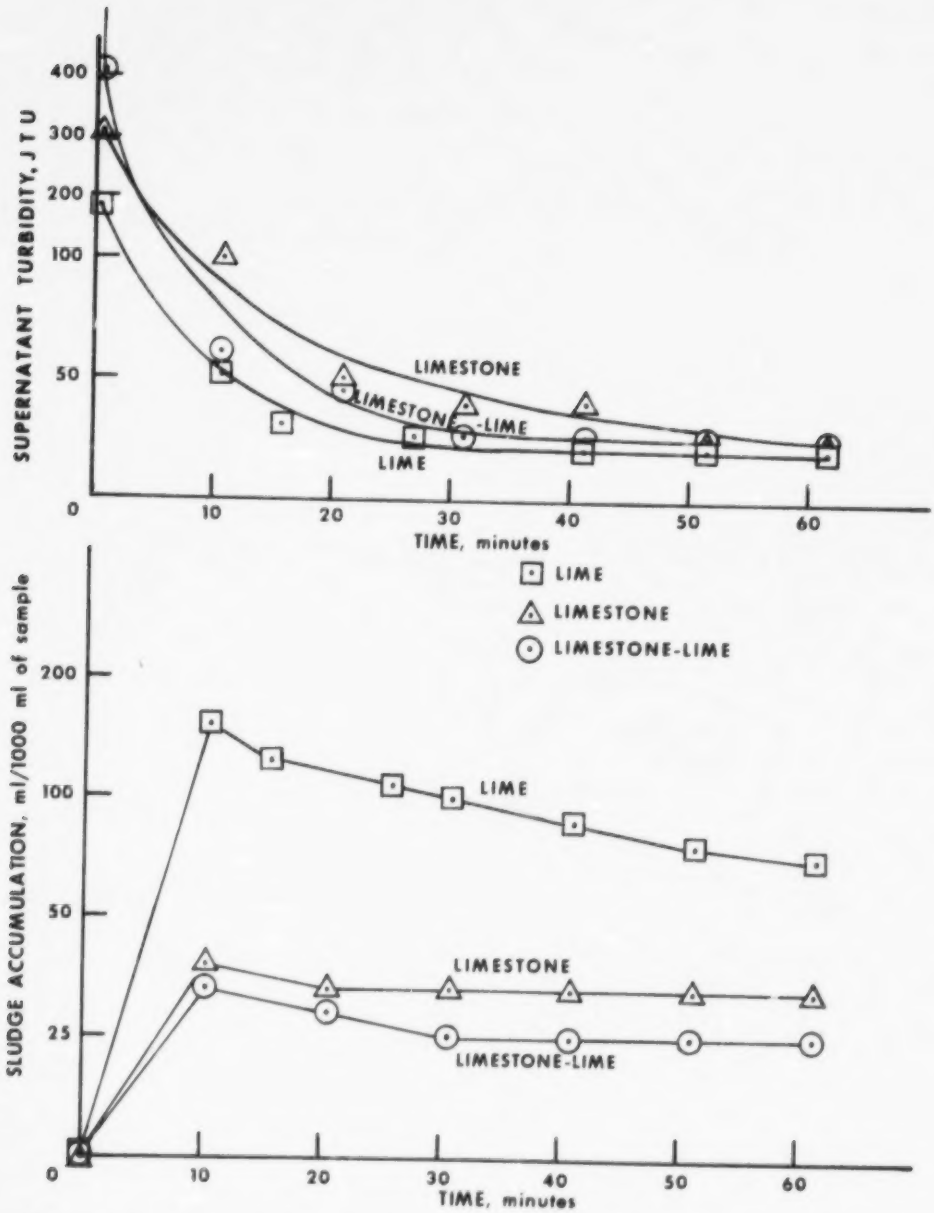


Figure 10. Supernatent turbidity and sludge buildup during settling. (All tests were conducted at pH 6.5.)

Advantages and Potentials of Combination Treatment

Compared to straight lime or limestone treatment, combination limestone-lime treatment provided greater than 25-percent reduction in material cost for treatment of the Norton AMD to pH 6.5. In addition to the cost advantage, combination treatment produced a sludge whose solids content was up to five times higher than sludge produced by lime neutralization, though not as high as sludge from limestone neutralization. Combination treatment was nearly as effective in clarification as lime and better than limestone. The volume of sludge produced by combination treatment was roughly one-third that of lime treatment and slightly less than limestone sludge volume. All three processes produced effluent waters of comparable quality.

Although this study was performed on a ferric iron water, the enormous potential of combination limestone-lime treatment of ferrous iron AMD is obvious.

In theory, combination limestone-lime treatment should be applicable to virtually all AMD situations. Whether or not an economic advantage can be realized is a matter that can only be determined by evaluating each individual site and its required process parameters. The variables that must be considered are:

1. Raw-material cost of rock-dust limestone and hydrated lime.
2. Effectiveness of limestone in AMD treatment (composition of stone).
3. Reaction time.
4. Treatment pH.

The effects of reaction time have already been discussed. Ford, Young, and Glenn[20] reported in detail on the effectiveness of various limestones in AMD treatment and suggested a simple test for stone evaluation. Raw material costs and treatment pH will be covered in the following discussion.

To determine the effects of raw-material costs for lime and limestone on process economics, usage data from Table 29 was chosen as an example. Both the lime and limestone raw-material costs were varied and the cost reduction calculated. A plot of the resulting data is given in Figure 11. When the lime/limestone raw-material cost ratio was less than 1.78:1, the cost advantage of combination treatment over lime treatment no longer existed. As the lime/limestone ratio increased, so did the advantage of combination treatment. At ratios below 1.78:1, lime was more economical.

Assuming the water treated in Table 26 were all ferrous iron AMD and a pH in the range of 9.0 were required for efficient oxidation by aeration, roughly 20 percent more lime would be required (verified by titration tests) to effect the pH increase from 6.4 to 9.0. Thus, Process B would require an additional 0.727 lbs/1000 gallons of lime (20 percent of 3.634) for a total of 4.361. The amount of limestone required by Process A would not change but the amount of lime would be increased by the same 0.727 pounds to 2.078 lbs/1000 gallons of water. In this example, cost reduction because of combination treatment would decrease to 21.4 percent at limestone = 0.30 cents/lb and lime = 0.90 cents/lb.

As in the previous case, raw-material costs for lime and for limestone were varied, and the resulting effect on combination-treatment cost advantage was calculated. Figure 12, Case I, presents a graph of this data. In this simulated ferrous iron situation, a lime/limestone raw-material cost ratio of 1.80:1 was the breakeven point. For ratios less than 1.80:1, lime was more economical and combination treatment gained rapid advantage as the ratio increased.

If 70 percent more lime were required to increase the pH from 6.5 to 9 (as was the case on a severely polluted ferrous water recently studied by the Norton staff), then the cost advantage of combination treatment over lime would decrease to 15.1 percent @ LS = 0.30 and L = 0.90 cents/lb and the breakeven lime/limestone raw-material cost ratio would again equal 1.80:1. These data are also presented in Figure 12, Case II.

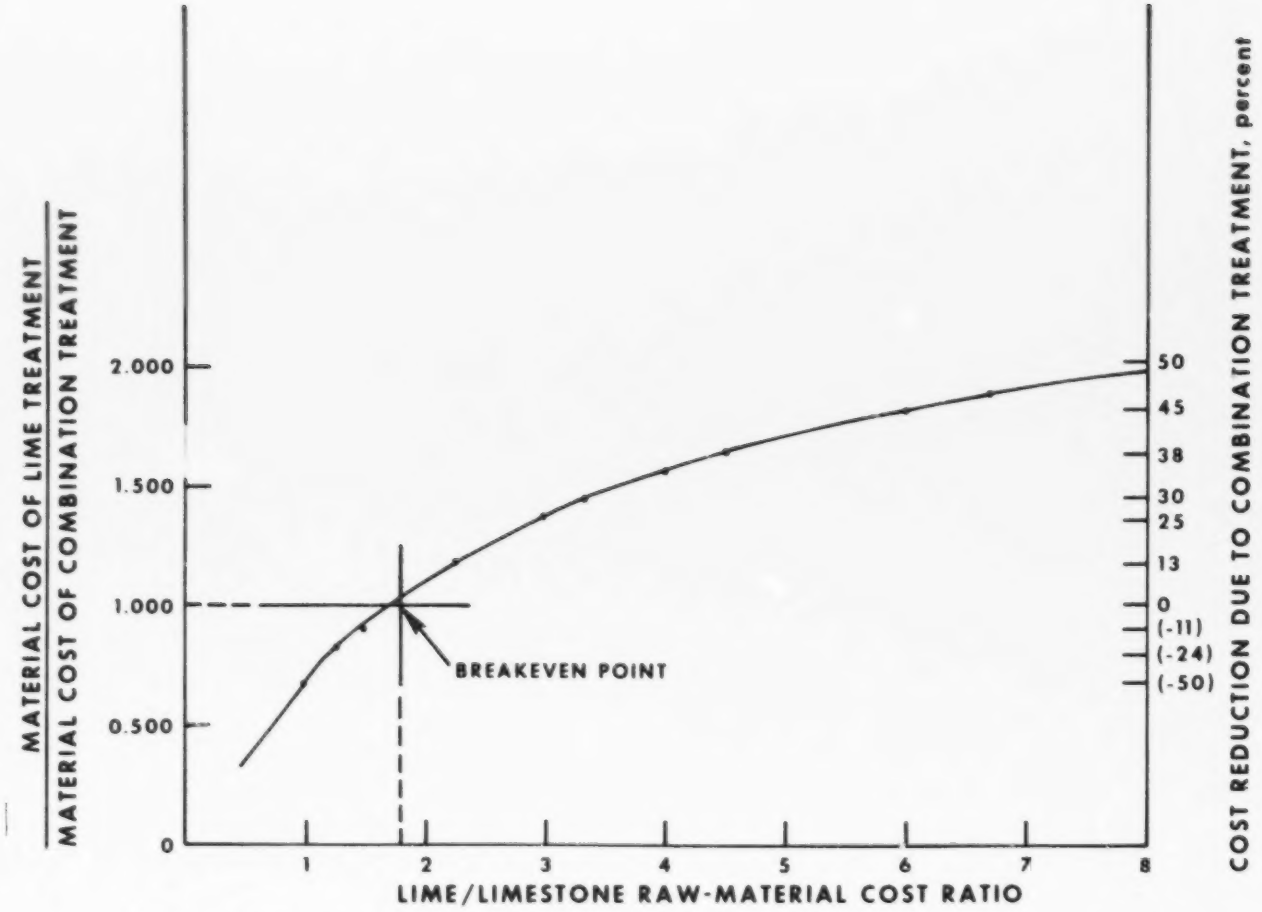


Figure 11. Effect of lime/limestone cost ratio on the economics of combination treatment.

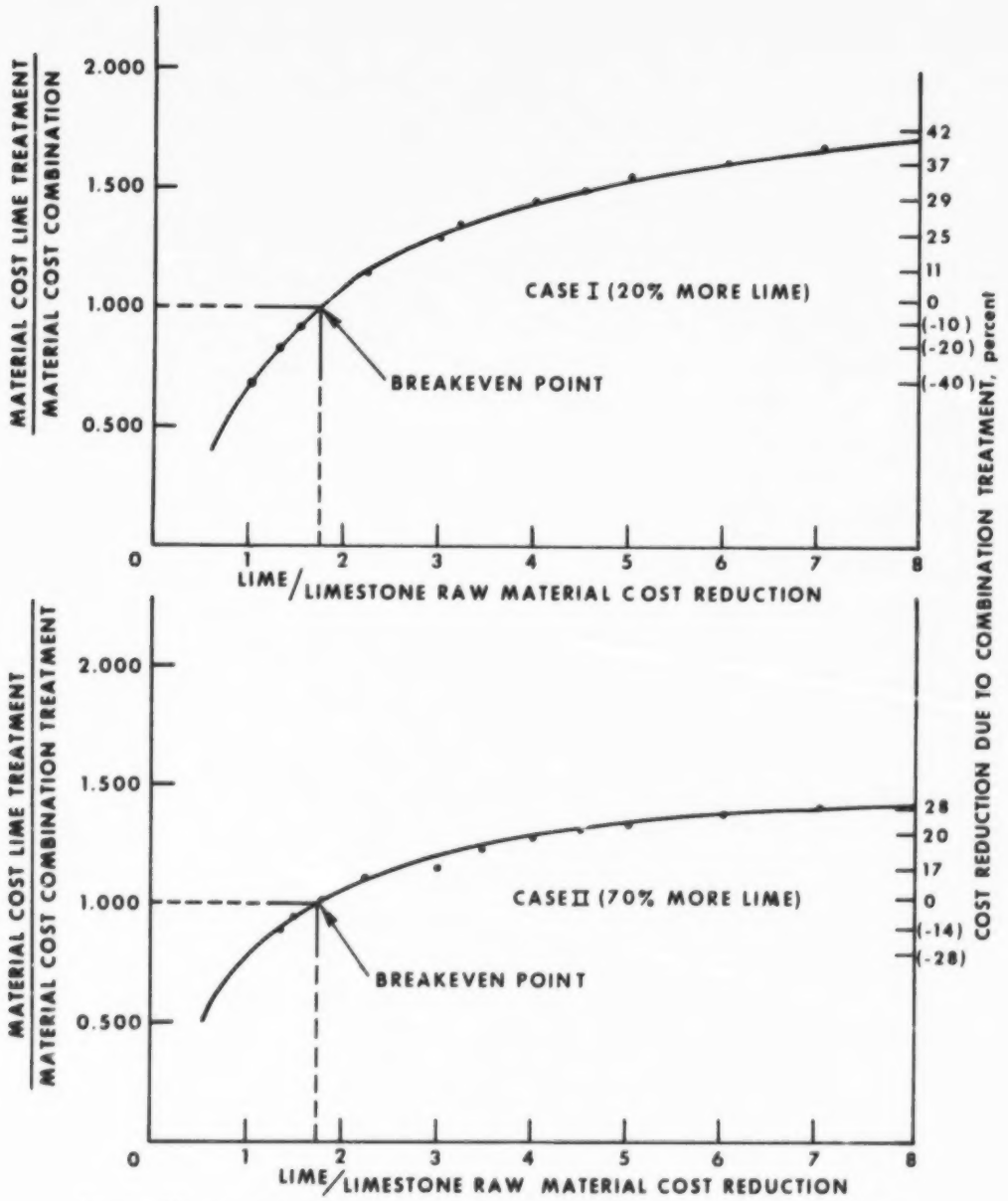


Figure 12. Lime/limestone cost ratio and process cost reduction at pH 9 (simulated).

In summary, combination treatment appears to offer nearly as great an economical advantage in ferrous iron situations as in ferric ones. This conclusion will be tested in future studies by EPA. Although combination treatment would require a higher initial investment in equipment, it is felt that the advantage realized in reagent cost reduction would quickly offset this increased initial expenditure. Simple batch tests could be performed on prospective waters to determine the feasibility of limestone-lime treatment in each specific situation.

SECTION VI

DISCUSSION

The effort to increase limestone utilization efficiency was moderately successful. Utilization efficiencies in the range of 50 to 60 percent were not as high as had been hoped for but were significant improvements over the early work at Norton,[5] where 32 percent was a typical value.

The results reported here correlate well with BCR's[27] findings in respect to efficiency, since BCR used twice the stoichiometric requirement for a utilization efficiency near 50 percent. BCR, however, used a smaller particle size (325 mesh) to enhance their efficiency somewhat to the 50-percent value.

Efficiencies as high as 65 percent were reported by Calhoun,[16] who used a rotary mill reactor on a predominately ferric iron water. The U.S. Bureau of Mines[13] (USBM) made no mention of limestone usage during their rotary mill study, but they did observe that the rotary reactor produced stone of extremely small particle size (89 percent passed 200 mesh) which may account for Calhoun's reported efficiency. Johns-Manville[30] used USBM's rotary mill reactor in their study at Osceola Mills, Pa., and reported utilization efficiencies for limestone of 34 percent. Lovell[21] performed a significant amount of work on rotary mill limestone neutralization and reported maximum utilization efficiencies as high as 80 percent. Lovell readily points out that accurate measurements of limestone usage in the rotary reactor configuration are very difficult to make and quite unreliable for precise calculations. Considering all the factors that surround the limestone reaction, it is felt that the high observed efficiencies credited to rotary mill application must be almost entirely due to particle size. Reaction time in Lovell's mill was 2 minutes. Mihok and Chamberlain's[13] rotary mill had 5 minutes, and Calhoun's had 3.5 minutes. Reaction times this short would be vastly inefficient if the particle size were not extremely small.

Lovell performed particle size analyses, not on the immediate reactor discharge (as did USBM) but on the settled sludge in the lagoon; he reported approximately 20 percent passing 325 mesh. Approximately 30 percent would not pass a 200-mesh screen (therefore, 70 percent did pass). In this report, only 30 percent of rock-dust limestone would pass a 200-mesh screen. It is apparent, therefore, that the high efficiencies observed by rotary mill reactors were indeed due to the rotary reactor grinding the stone to extremely fine particle size and thus enhancing reactivity. Of course, the rotary action constantly removed reaction coatings from the stones to expose fresh reaction surfaces. Rotary reactors appear to be a promising method for limestone treatment of AMD.

Holland et al.,[19] used rock dust to treat a ferrous discharge and reported that a 30-percent excess of limestone was required. This works out to a utilization efficiency near 80 percent. A sieve analysis of Holland's rock dust indicated 67.3 percent would pass a 325-mesh screen--hence the high efficiency.

Holland went on to postulate that the apparent limestone sludge density and volume advantage over lime sludge would be "more imaginative than real" since lime sludge, when continually decanted, will vastly decrease in volume over extended periods of time. Although Holland had no figures on limestone sludge, he felt it would not react the same way. There has been a great deal of emphasis from EPA--as well as from independent researchers--on diminishing the sludge volume (even by highly sophisticated techniques such as vacuum filtration and centrifugation) in order to increase land use efficiency and reduce costs of disposal. In most instances, it seems impractical to store and decant sludge for extended periods, as Holland suggests. It is felt that the immediate advantages of limestone sludge are indeed real and important characteristics of the limestone process.

Both Calhoun[16] and Holland[19] suggested the use of combination limestone/hydrated-lime treatment. Holland performed some studies on the process but failed to cite any particular advantages (although he recommended its use on ferrous iron waters). Combination limestone/hydrated-lime treatment[28][32] has been used since 1957 in Japan in AMD

treatment of unusually high concentrations of iron (as high as 6000 mg/l). Ikegami[28] reported first-step limestone requirements of 0.8 times the stoichiometric requirement followed by 2.0 times the stoichiometric requirement for lime addition. He further recommended a limestone reaction time of 20 to 30 minutes. Ikegami points out that combination treatment has been used since 1957 instead of lime treatment, since sludge volume to be stored was reduced to a minimum. His treatment scheme is tailored toward byproduct removal as well as pollution abatement, since he selectively precipitates iron, calcium sulfate, and aluminum during the treatment process.

Various researchers have published cost figures for neutralization of AMD. Table 33 contains a summary of selected results on various types of waters, as well as various treatment techniques. These reported costs represent chemical costs for the neutralizing reagents used--not total cost of treatment--and have been converted to cost per mg/l of acidity per million gallons of water for direct comparison. No corrections were made for variations in raw-material costs between the individual reports. Soda ash costs were inordinately high at 40 to 50 cents per mg/l acidity per million gallons. Good correlation was observed between the results of independent researchers on soda ash. Reported lime costs ranged from 5.3 to 8.5 cents. Rock-dust limestone costs were on the same order as lime, with a range of 5.8 to 9.8 cents per mg/l acidity per million gallons. Agreement between researchers in both of these areas was also good. Combination limestone/hydrated-lime costs of 4.3 cents ranked second only to rotary mill limestone treatment, whose costs ranged from 1.8 to 2.8 cents per mg/l acidity per million gallons treated. Agreement between Lovell[21] and Calhoun[16] on rotary mill results was also good.

Estimates of <u>total</u> treatment costs for neutralization (given in Table 34) ranged from 8.7 cents per 1000 gallons for lime treatment at Morea Strip Pit to $1.28 per 1000 gallons for lime treatment at Bethlehem Mines Marianna No. 58 Mine. Limestone costs ranged from 13.6 to 76 cents per 1000 gallons. Johns-Manville[30] showed a significant cost advantage for combination limestone/hydrated-lime treatment as compared to lime

Table 33. COMPARISON OF REAGENT COSTS FOR TREATING MINE DRAINAGE

Source	Type Treatment	Acidity mg/l	Chemical Costs Cents /1000 Gal.	Chemical Costs Cents per mg/l acidity/10^6 G.	Raw Material Cost
Corsaro, et al[17]	Lime - Ferrous Iron	1400	11.0	7.9	@ $22.00 ton bulk
Corsaro, et al[17]	Lime - Ferrous Iron	650	5.5	8.5	@ $22.00 ton bulk
Wilmoth & Hill[5]	Limestone (Rock Dust) - Ferric	600	5.9	9.8	@ $6.00 ton bags
Wilmoth & Hill[5]	Lime - Ferric Iron	600	3.2	5.3	@ $17.00 ton bags
Wilmoth & Hill[5]	Soda Ash - Ferric Iron	550	26.8	48.7	@ $100.00 ton bags
Ford[27]	Limestone (Recycle Sludge) - Fe^{2+}	190	1.1	5.8	N. A.
Lovell[21]	Lime - Ferrous Iron	513	3.4*	6.6*	@ $20.00 ton bulk*
Lovell[21]	Soda Ash - Ferrous Iron	567	25.1*	44.2*	@ $100.00 ton bags*
Lovell[21]	Limestone - Rotary Mill - Fe^{2+}	1500	2.7	1.8	@ $3.28 ton bulk
Calhoun[16]	Limestone - Rotary Mill - Fe^{3+}	360	1.0	2.8	@ $4.60 ton bulk
This Report	Limestone (Rock Dust) - Fe^{3+}	560	3.4	6.1	@ $6.00 ton bags
This Report	Lime	570	3.3	5.7	@ $18.00 ton bags
This Report	Combination Limestone - Lime	570	2.4	4.3	Ls-$6.00 ton bags @ L-$18.00 ton bags

*Assuming: Lime cost of $20.00 per ton bulk
Soda Ash cost of $100.00 per ton bags

Note: To convert from cents/1000 gal to cents/cu m, multiply by 0.264.

Table 34. ESTIMATES OF TOTAL TREATMENT COSTS

Source	Type Treatment	Cost /1000 Gal, cents	Remarks
Draper[31]	Lime	19.9	Duquesne Light, Warwick #2 Mine 3,500,000 gpd, acidity = 1550 mg/l
Corsaro, et al[17]	Lime	33.0	900,000 gpd, acidity = 1400 mg/l
Tybout[29]	Lime	108.7	Bethlehem Marianna #58 Mine A 240,000 gpd, acidity = 4080 mg/l
Tybout[29]	Lime	127.9	Bethlehem Marianna #58 Mine B 300,000 gpd, acidity = 8150 mg/l
Tybout[29]	Lime	72.2	Young and Son Coal Mine 180,000 gpd, acidity = 770 mg/l
Tybout[29]	Lime	8.7	Morea Strip Pit 4,000,000 gpd, acidity = 190 mg/l
Tybout[29]	Lime	22.6	Blue Coal Loomis #4 5,760,000 gpd, acidity = 560 mg/l
Tybout[29]	Lime	53.7	Duquesne Light Warwick #3 North 600,000 gpd, acidity = 1250 mg/l
Lovell[21]	Rotary Mill Limestone	76.0	Hollywood Site, Proctor #2 Water 86,400 gpd, acidity = 1500 mg/l
Ford[27]	Ground Limestone	13.6	4,000,000 gpd, acidity = 190 mg/l
Johns-Manville[30]	Rotary Mill Limestone	15.0	Hollywood Site - Bennett Branch Water 1,500,000 gpd, acidity = 337 mg/l
Johns-Manville[30]	Limestone - Lime	20.0	Rotary Mill Limestone - Bennett Branch 1,500,000 gpd, acidity = 337 mg/l
Johns-Manville[30]	Limestone - Magnesite	15.0	Rotary Mill Limestone - Bennett Branch 1,500,000 gpd, acidity = 337 mg/l
Johns-Manville[30]	Lime	116.0	Hollywood Site, Proctor #2 Water 1,500,000 gpd, acidity = 1740 mg/l
Johns-Manville[30]	Limestone - Lime	77.0	Hollywood Site, Proctor #2 Water 1,500,000 gpd, acidity = 1740 mg/l

Note: To convert from cents/1000 gal to cents/cu m, multiply by 0.264.

treatment on Hollywood's Proctor No. 2 water (limestone/hydrated-lime cost 77 cents per 1000 gallons and lime cost $1.16 per 1000 gallons) for a 34-percent cost reduction. This was slightly better than the 25-percent cost advantage noted in this report.

SULFATE-CONDUCTIVITY CORRELATION

During the course of studies at Norton and at a temporary test site in Pennsylvania, a significant volume of sulfate data was collected under a variety of conditions. An attempt was made to correlate the sulfate and conductivity parameters. The resulting data plots and fourth-order regression analysis lines of best fit are given in Figures 13 and 14. Considerable scatter is apparent in the data points for both sites. Dr. Lovell,[21] of Pennsylvania State University, considered the same correlation on four test waters at Hollywood, Pa., and found a surprisingly good correlation. There was considerably less scatter in Lovell's data for two reasons: First, Lovell used a gravimetric sulfate technique that was superior in accuracy and precision to the turbidimetric method used at Norton; and second, the variation in Lovell's test conditions was probably not as great as those used by EPA.

A direct comparison of Lovell's and EPA's correlation is shown in Figure 15. The general trend of both relationships was the same. Conductivity may be useful as an indirect sulfate measurement technique.

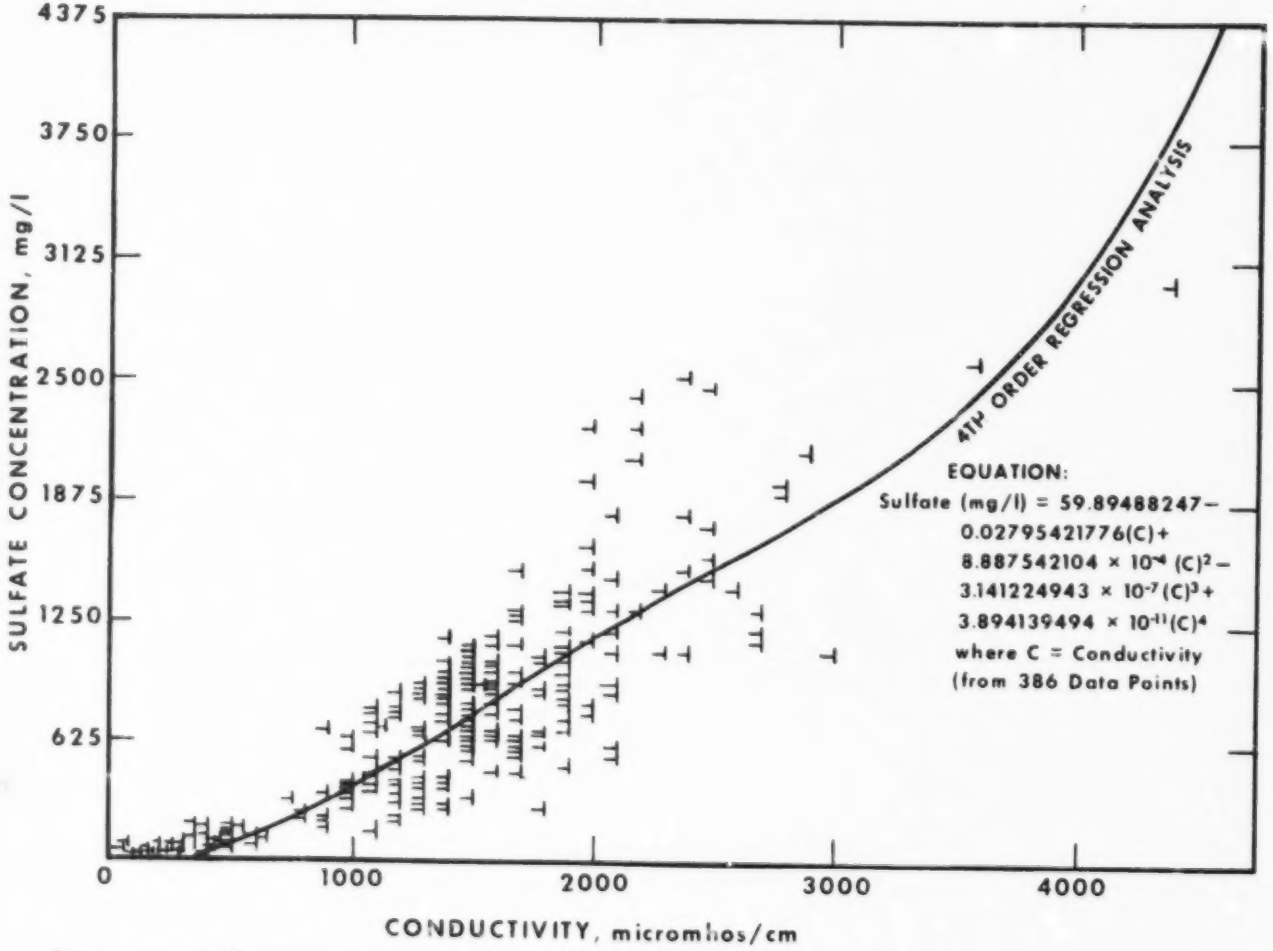


Figure 13. Sulfate-conductivity relationship at Norton, West Virginia.

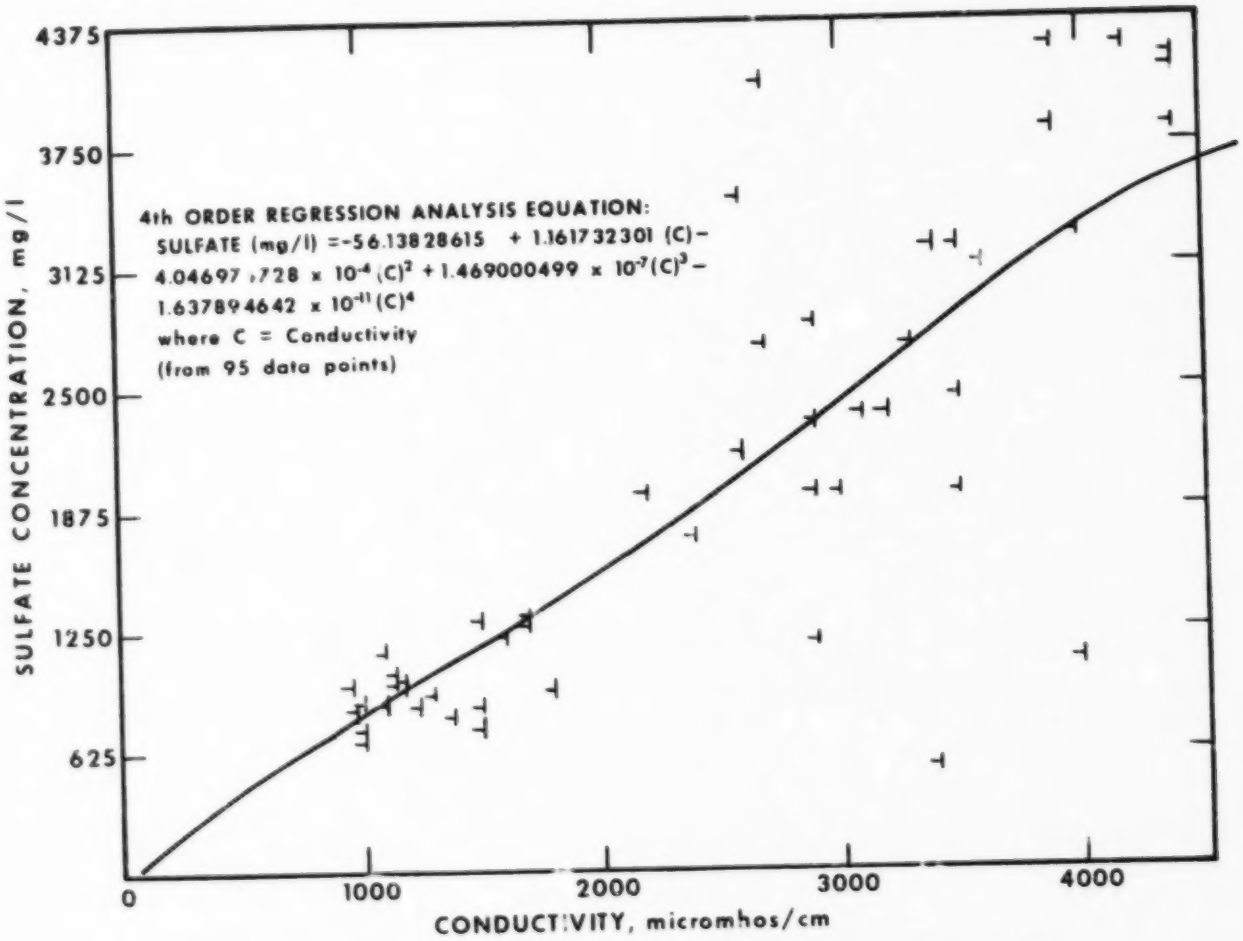


Figure 14. Sulfate-conductivity relationship at Mocanaqua, Pa.

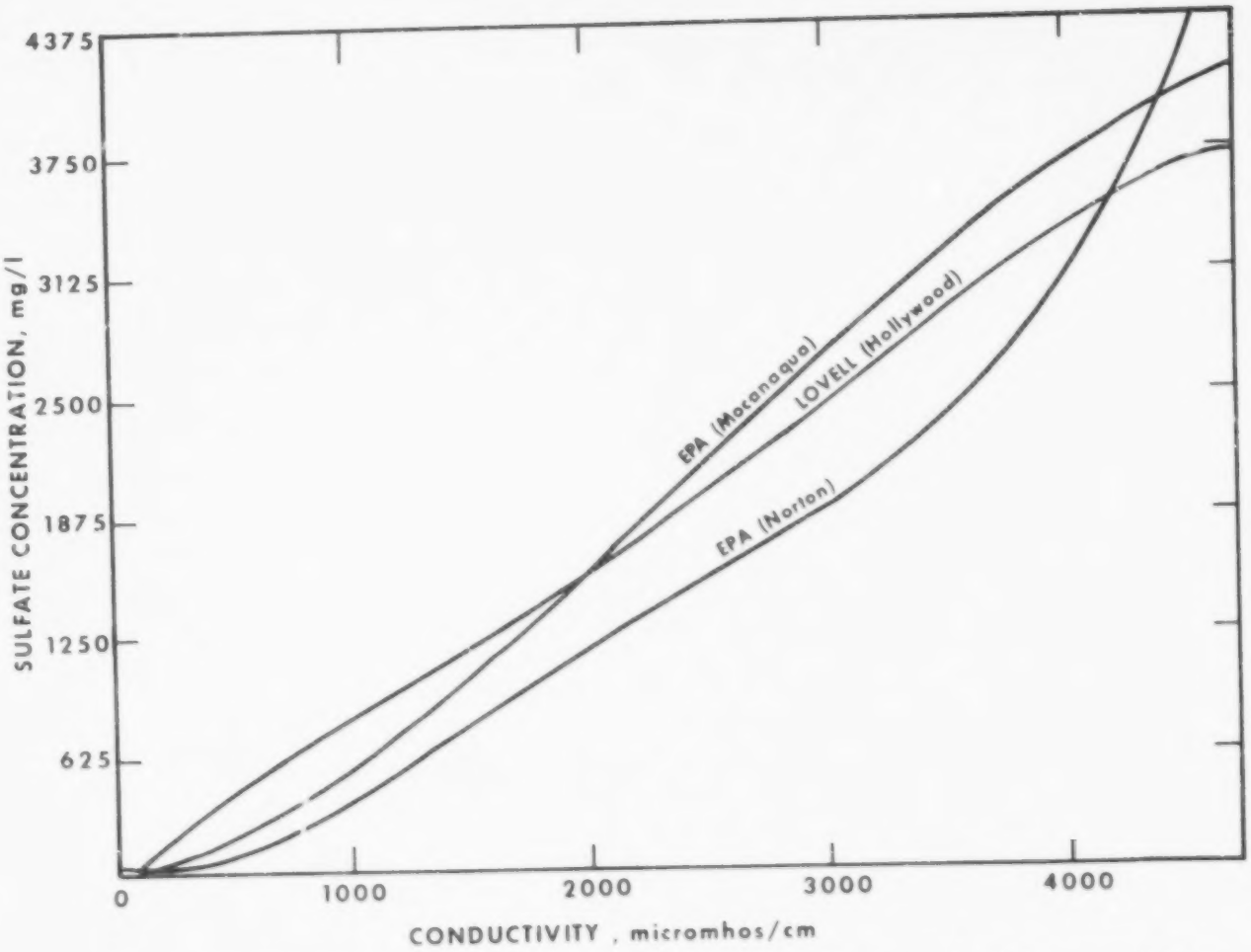


Figure 15. Comparison between EPA and Lovell's sulfate-conductivity correlation.

SECTION VII

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SECTION VIII

GLOSSARY

CALCULATIONS AND DEFINITIONS

Mean Probable Detention Time: A mathematical approximation of the average actual time a flowing liquid is detained in a vessel. The value is determined by tracer studies in which the tracer concentration exiting from the tank is monitored in respect to time. Two values are plotted on probability paper for each measurement point, i.e., cumulative tracer quantities to each point ÷ total cumulative tracer quantity measured (percent passing) and the ratio of elapsed time of each measurement ÷ theoretical detention time of the vessel. The theoretical time equals the tank volume divided by the flow rate. The resulting probability plot is interpolated to derive the time for 50 percent passing.

Detention Efficiency: The ratio of mean probable detention time to theoretical detention time expressed as a percentage.

Utilization Efficiency: A measure of the proportion of a neutralizer that reacts with the acid water as compared to the amount originally added. Since alkalinity imparted to the water is considered a benefit, the formula for utilization efficiency is:

$$\text{Utilization Efficiency} = \frac{\text{Alkalinity Used}}{\text{Alkalinity Added}}$$

therefore,

$$\text{Utilization Efficiency} = \frac{\text{Influent Acidity - Effluent Acidity + Effluent Alkalinity (as } CaCO_3\text{)}}{\text{Alkalinity Added (as } CaCO_3\text{)}} \times 100$$

Stoichiometric Factor: The ratio of amount of neutralizer required to treat original amount of acid present:

$$\text{Stoichiometric Factor} = \frac{\text{Alkalinity Added (as } CaCO_3\text{)}}{\text{Influent Acidity (as } CaCO_3\text{)}}$$

Statistically Significant Differences: It was desirable to determine mathematically if the apparent differences between Process A and Process B were truly due to the variable under study or just to random variation. A statistical test was chosen to assist in data evaluation. The test used was the paired observation t test, which calculated a test statistic t from the differences between paired measurements of Processes A and B of the neutralization system. The 95-percent confidence level was used. When the calculated statistic t exceeded the value from t tables, a significant difference between the processes was indicated. If the calculated value was less than the table value, it was not possible to say that the means of the two processes differed (hence was not significant at the specified confidence level).

SECTION IX

APPENDIX

Table 35. CHEMICAL ANALYSES FOR VARIABLE pH STUDY

Sample	pH at Time of Analysis	Acidity as $CaCO_3$	Cond.	Ca	Mg	Al	Total Iron	SO_4	Alk.	Turb.	pH When Sample was Taken
April 28, 1970											
Raw Feed	2.3	440	1300	120	33	34	88	790	0	-	2.3
Pool B	7.1	0	1000	380	33	0.3	0.7	750	78	10*	7.0
April 29, 1970											
Raw Feed	2.4	450	1300	105	33	30	92	760	-	-	2.4
Pool A	6.4	2	1000	300	33	1.0	2.3	820	24	29	6.1
Pool B	4.8	30	1000	280	33	6	2.3	820	1.0	53	5.1
April 30, 1970											
Raw Feed	2.4	470	1400	130	33	36	120	870	-	-	2.4
Pool A	5.3	25	1100	380	33	2	4	870	2	44	5.6

*Estimated

NOTE: All units are mg/l except for pH, conductivity (micromhos/cm), and turbidity (JTU).

Table 36. EFFECT OF DETENTION TIME - 15 GPM (56.8 L/M) VS 10 GPM (37.9 L/M)

	PROCESS A = 15 GPM		PROCESS B = 10 GPM		
Date	Effluent pH	Limestone Usage, #/1000 gal.	Effluent pH	Limestone Usage, #/1000 gal.	Percent Reduction in Limestone Usage
6/2/70	5.1	8.03	4.9	6.59	17.9
6/2/70	5.0	7.89	4.9	7.54	4.4
6/3/70	4.9	8.00	5.0	7.61	4.9
6/17/70	5.1	6.55	4.8	5.55	15.3
6/17/70	5.1	6.11	5.0	5.56	9.0
6/18/70	5.1	6.35	4.8	5.45	14.2
6/19/70	5.1	9.59	4.8	9.42	1.8
Means	5.1	7.50	4.9	6.82	9.1

Typical Utilization Efficiencies:
Process A = 46% Process B = 51%

Statistical Analysis
t limits from tables ± 2.447
t calculated from data -4.06

Was difference significant? Yes X No ___

	Process A		Process B	
Date	Iron	Turbidity	Iron	Turbidity
6/2/70	8.0 mg/l	48 JTU	4.0 mg/l	18 JTU
6/2/70	14	79	4.8	26
6/3/70	2.4	43	2.0	22
6/17/70	1.6	57	1.0	41
6/17/70	1.4	39	1.6	21
6/18/70	2.6	36	1.2	28
6/19/70	5.2	42	2.5	29

Note: To convert from lbs/1000 gal to kg/cu m, multiply by 0.120.

Table 37. EFFECT OF DETENTION TIME - 15 GPM (56.8 L/M) VS 5 GPM (18.9 L/M)

	PROCESS A = 15 GPM		PROCESS B = 10 GPM		
Date	Effluent pH	Limestone Usage, #/1000 gal.	Effluent pH	Limestone Usage, #/1000 gal.	Percent Reduction in Limestone Usage
5/7/70	5.0	7.12	5.0	5.77	18.9
5/8/70	5.3	5.34	5.0	5.02	6.0
5/25/70	6.0	8.71	5.9	7.41	14.9
5/26/70	4.8	6.62	5.1	5.56	16.0
5/27/70	4.6	7.56	4.7	6.51	13.9
5/28/70	4.9	6.68	4.9	6.39	4.3
Means	5.1	7.01	5.1	6.11	12.8

Typical Utilization Efficiencies:
Process A = 47% Process B = 55%

Statistical Analysis
t limits from tables ± 2.571
t calculated from data -4.63

Was difference significant? Yes X No ___

EFFLUENT QUALITY

	Process A		Process B	
Date	Iron	Turbidity	Iron	Turbidity
5/7/70	7 mg/l	42 JTU	1.6 mg/l	10 JTU
5/25/70	5	21	3	12
5/26/70	6	65	6	16
5/27/70	15	68	2.8	13

Note: To convert from lbs/1000 gal to kg/cu m, multiply by 0.120.

Table 38. EFFECT OF DETENTION TIME - TWO REACTORS IN SERIES VS ONE REACTOR

	Process A = Two reactors in Series @ 15 gpm		Process B = One reactor @ 15 gpm		
Date	Effluent pH	Limestone Usage, #/1000 gal.	Effluent pH	Limestone Usage, #/1000 gal.	Percent Reduction in Limestone Usage
10/23/70	5.1	5.53	5.0	5.78	4.3
10/28/70	5.0	5.74	5.0	6.32	9.2
11/10/70	5.1	3.66	5.1	3.82	4.2
11/10/70	5.0	3.88	5.1	4.47	13.2
11/11/70	5.0	4.91	5.1	4.99	1.6
11/12/70	5.0	5.26	5.2	5.97	11.9
Means	5.0	4.83	5.1	5.23	7.6

Typical Utilization Efficiencies:
Process A = 59% Process B = 54%

Statistical Analysis
t limits from tables ± 2.571
t calculated from data +3.673

Was difference significant? Yes X No ___

EFFLUENT QUALITY

	Process A		Process B	
Date	Iron	Turbidity	Iron	Turbidity
10/23/70	3.0 mg/l	58 JTU	3.0 mg/l	57 JTU
10/28/70	4.0	50	4.0	52
11/10/70	14	76	20	78
11/10/70	5.0	76	5.0	80
11/11/70	10	68	15	80
11/12/70	-	59	-	36

Note: To convert from lbs/1000 gal to kg/cu m, multiply by 0.120. To convert from gpm to liters/minute, multiply by 3.785.

Table 39. EFFECT OF DETENTION TIME - TWO REACTORS IN SERIES @ 5 GPM VS ONE REACTOR @ 15 GPM

	Process A = Two reactors in Series @ 5 GPM		Process B = One reactor @ 15 GPM		
Date	Effluent pH	Limestone Usage, #/1000 gal.	Effluent pH	Limestone Usage, #/1000 gal.	Percent Reduction in Limestone Usage
12/2/70	5.2	8.53	5.2	9.09	6.2
12/3/70	5.2	6.71	5.2	9.58	30.0
12/4/70	5.2	6.79	5.3	8.73	22.2
12/16/70	5.4	5.06	5.4	6.19	18.3
Means	5.3	6.77	5.3	8.40	19.4

Typical Utilization Efficiencies:
Process A = 62% Process B = 47%

Statistical Analysis
t limits from tables ± 3.182
t calculated from data +3.23

Was difference significant? Yes X No___

Effluent Quality

	Process A		Process B	
Date	Iron	Turbidity	Iron	Turbidity
12/2/70	8 mg/l	30 JTU	12 mg/l	48 JTU
12/3/70	8	18	12	43
12/4/70	4	41	14	56
12/16/70	8	35	8	76

Note: To convert from lbs/1000 gal to kg/cu m, multiply by 0.120. To convert from gpm to liters/minute, multiply by 3.785.

Table 40. CHEMICAL ANALYSES FOR DETENTION TIME STUDY

Sample	pH at Time of Analysis	Acidity as $CaCO_3$	Cond.	Ca	Mg	Al	Total Iron	SO_4	Alk.	Turb.	pH when Sample was Taken
6/2/70 thru 6/19/70											
Raw Feed	2.8	380	1700	130	39	34	105	1050	-	-	
Pool A	4.9	25	1350	320	39	6.0	5.7	940	1	56	5.0
Pool B	4.9	28	1350	320	40	6.9	2.8	940	1	26	4.9
5/7/70 thru 5/27/70											
Raw Feed	2.7	440	1700	120	37	37	110	1050	-	-	
Pool A	5.0	20	1400	330	38	9	10.0	950	8	37	5.1
Pool B	5.0	20	1350	320	37	6.4	3.9	950	5	25	5.1
10/23/70 thru 11/12/70											
Raw Feed	2.9	380	1000	190	97	205	67	580	-	-	
Pool A	5.0	15	870	450	85	6.5	13	540	1	65	5.0
Pool B	5.0	16	850	470	85	8	14	530	1	64	5.1
12/2/70 thru 12/16/70											
Raw Feed	2.8	520	1300	160	57	190	72	850	-	-	
Pool A	5.0	17	1200	430	54	7	7	660	2	31	5.3
Pool B	5.0	13	1150	430	53	12	12	640	1	56	5.3

NOTE: All units are mg/l except for pH, conductivity (micromhos/cm), and turbidity (JTU).
All values are means from individual data sets.

Table 41. EFFECT OF REACTOR BAFFLES @ 15 GPM (56.8 LITERS/MIN)

	PROCESS A = Two Wooc Baffles @ 15 gpm		PROCESS B = No Baffles - 15 gpm		
Date	Effluent pH	Limestone Usage, #/1000 gal.	Effluent pH	Limestone Usage, #/1000 gal.	Percent Reduction in Limestone Usage
7/1/70	4.7	7.63	4.8	7.96	4.1
7/2/70	4.9	7.18	5.0	8.32	13.7
7/8/70	5.1	8.17	5.2	9.35	12.6
Means	4.9	7.66	5.0	8.54	10.3

Typical Utilization Efficiencies:
Process A = 56% Process B = 52%

Statistical Analysis
t limits from tables ± 4.303
t calculated from data +3.19

Was difference significant? Yes ___ No X

Effluent Quality

	Process A		Process B	
Date	Iron	Turbidity	Iron	Turbidity
7/1/70	2.0 mg/l	35 JTU	2.5 mg/l	50 JTU
7/2/70	2.0	33	2.5	43
7/3/70	2.0	32	2.4	33

Note: To convert from lbs/1000 gal to kg/cu m, multiply by 0.120.

Table 42. COMPARISON OF WOOD AND SCREEN BAFFLES AT 15 GPM (56.8 LITERS/MIN)

Date	Process A = Two wood baffles @ 15 gpm: Effluent pH	Process A: Limestone Usage, #/1000 gal.	Process B = Two fine mesh screen baffles @ 15 gpm: Effluent pH	Process B: Limestone Usage, #/1000 gal.	Percent Reduction in Limestone Usage
7/21/70	5.1	5.31	5.2	4.98	6.2
7/22/70	5.2	5.82	5.2	5.47	6.0
7/22/70	5.2	5.82	5.0	5.71	1.9
7/23/70	5.2	6.66	5.0	6.02	9.6
Means	5.2	5.90	5.1	5.55	5.9

Typical Utilization Efficiencies:
Process A = 55% Process B = 58%

Statistical Analysis
t limits from tables ± 3.182
t calculated from data -3.288

Was difference significant? Yes X No ___

Effluent Quality

Date	Process A: Iron	Process A: Turbidity	Process B: Iron	Process B: Turbidity
7/21/70	4.5 mg/l	68 JTU	4.8 mg/l	65 JTU
7/22/70	4.2	28	3.7	28
7/22/70	1.6	40	2.0	90
7/23/70	2.8	40	2.8	80

Note: To convert from lbs/1000 gal to kg/cu m, multiply by 0.120.

Table 43. EFFECT ON SCREEN-BAFFLE MESH SIZE AT 15 GPM (56.8 LITERS/MIN)

	Process A = Two large mesh screen baffles @ 15 gpm		Process B = Two small mesh screen baffles @ 15 gpm		
Date	Effluent pH	Limestone Usage, #/1000 gal.	Effluent pH	Limestone Usage, #/1000 gal.	Percent Reduction in Limestone Usage
8/27/70	4.9	7.87	5.0	8.38	6.1
8/28/70	4.8	8.80	5.0	10.41	15.5
Means	4.9	8.34	5.0	9.40	11.3

Typical Utilization Efficiencies:
Process A = 60% Process B = 55%

Statistical Analysis
t limits from tables ± 12.706
t calculated from data ± 1.927

Effluent Quality

	Process A				Process B			
Date	Iron		Turbidity		Iron		Turbidity	
8/27/70	2.1	mg/l	30	JTU	1.0	mg/l	30	JTU
8/28/70	2.4		35		1.2		35	

Was difference significant? Yes ___ No X*

*Too few samples.
Note: To convert from lbs/1000 gal to kg/cu m, multiply by 0.120.

Table 44. COMPARISON OF THREE VS TWO WIRE-MESH BAFFLES AT 15 GPM (56.8 LITERS/MIN)

	Process A = Three large mesh screen baffles @ 15 gpm		Process B = Two large mesh screen baffles @ 15 gpm		
Date	Effluent pH	Limestone Usage, #/1000 gal.	Effluent pH	Limestone Usage, #/1000 gal.	Percent Reduction in Limestone Usage
9/16/70	5.0	11.27	4.9	9.22	18.2
9/17/70	5.1	9.29	5.0	9.39	1.1
9/17/70	5.0	9.60	4.9	9.27	3.4
10/7/70	5.0	8.64	5.1	8.00	7.4
10/9/70	5.0	8.89	5.2	9.07	2.0
10/9/70	5.1	8.81	5.1	8.89	0.9
Means	5.0	9.42	5.0	8.97	4.8

Typical Utilization Efficiencies;
Process A = 55% Process B = 56%

Statistical Analysis

t limits from tables ± 2.571
t calculated from data ± 1.281

Was difference significant? Yes ___ No X

Effluent Quality

Date	Process A Iron	Process A Turbidity	Process B Iron	Process B Turbidity
9/16/70	--	27 JTU	--	36 JTU
9/17/70	5.2 mg/l	31	5.0 mg/l	30
9/17/70	9.2	38	8.1	38
10/7/70	12	52	14	58
10/9/70	10	34	12	39
10/9/70	9.0	48	10	52

Note: To convert from lbs/1000 gal to kg/cu m, multiply by 0.120.

Table 45. CHEMICAL ANALYSES FOR BAFFLE STUDY

Sample	pH at Time of Analysis	Acidity as $CaCO_3$	Cond.	Ca	Mg	Al	Total Iron	SO_4	Alk.	Turb.	pH when sample was taken
7/1-8/70											
Raw Feed	2.7	610	1870	180	56	42	130	1000	-	-	2.7
Pool A	4.8	43	1400	430	57	9.7	2.0	860	2	33	4.9
Pool B	5.0	41	1450	440	59	9.7	2.5	860	2	42	5.0
7/21-23/70											
Raw Feed	2.9	450	1400	120	40	35	95	780	-	-	2.9
Pool A	4.9	39	1100	300	40	4.3	3.2	720	2	44	5.2
Pool B	4.8	50	1100	300	41	8.4	3.3	720	2	66	5.1
8/27-28/70											
Raw Feed	2.8	610	1650	170	57	50	120	1050	-	-	2.8
Pool A	5.0	3.5	1250	410	60	3.8	2.3	1050	2	32	4.9
Pool B	5.6	1.5	1250	430	59	1.0	1.1	1050	2	32	5.0
9/16-10/9/70											
Raw Feed	2.7	630	1670	230	78	59	170	1270	-	-	2.7
Pool A	4.9	26	1400	590	74	8.6	9.1	910	2	38	5.0
Pool B	5.0	26	1380	610	75	8.4	10	780	2	42	5.0

NOTE: All units are mg/l except for pH and conductivity (micromhos/cm).
All values are means from individual data sets.

Table 46. CHEMICAL ANALYSES FOR 400-MESH LIMESTONE STUDY

Sample	pH at time of analysis	Acidity as $CaCO_3$	Cond.	Ca	Mg	Al	Total Iron	SO_4	Alk.	Turb.	pH when sample was taken
2/9-12/71											
Raw Feed	2.9	400	1200	100	33	28	130	575	-	-	2.9
Pool A	5.1	19	900	300	36	7.5	8.0	520	10	61	5.1
Pool B	5.1	17	900	330	35	5.0	9.1	540	10	77	5.2
2/24-26/71											
Raw Feed	2.9	360	900	150	50	52	180	640	-	-	2.9
Pool A	4.9	19	700	460	48	7.3	5.5	530	1	35	5.1
Pool B	4.9	11	730	450	48	7.8	4.8	510	2	42	5.0
3/31-4/3/71 - Sludge Recirculation Study											
Raw Feed	2.9	400	950	95	28	34	3	570	-	-	2.9
Pool A	4.9	9.0	720	240	27	4.3	4.8	430	2	52	5.0
Pool B	5.2	5.2	730	260	27	4.0	7.3	450	4	69	5.1

NOTE: All units are mg/l except for ph, conductivity (micromhos/cm), and turbidity (JTU).
All values are means from individual data sets.

Table 47. CHEMICAL ANALYSES FOR LIME VS LIMESTONE STUDY

Sample	pH at time of analysis	Acidity as $CaCO_3$	Cond.	Ca	Mg	Al	Total Iron	SO_4	Alk.	Turb.	pH when sample was taken
10/19-29/71											
Raw Feed	2.6	720	1790	110	40	41	120	1200	-	-	2.6
Pool A	6.5	5.0	1570	300	39	0.8	2.1	1100	80	12	6.4
Pool B	6.2	9.0	1550	290	30	1.3	1.9	1120	18	7	6.4
11/16-21/71											
Raw Feed	2.5	680	1840	150	52	48	130	1080	-	-	2.5
Pool A	6.5	4	1510	420	53	0.5	0.9	1010	74	12	6.5
Pool B	6.5	6	1470	410	43	1.2	1.4	1030	15	5	6.5

NOTE: All units are mg/l except for pH, conductivity (micromhos/cm), and turbidity (JTU).
All values are means from individual data sets.